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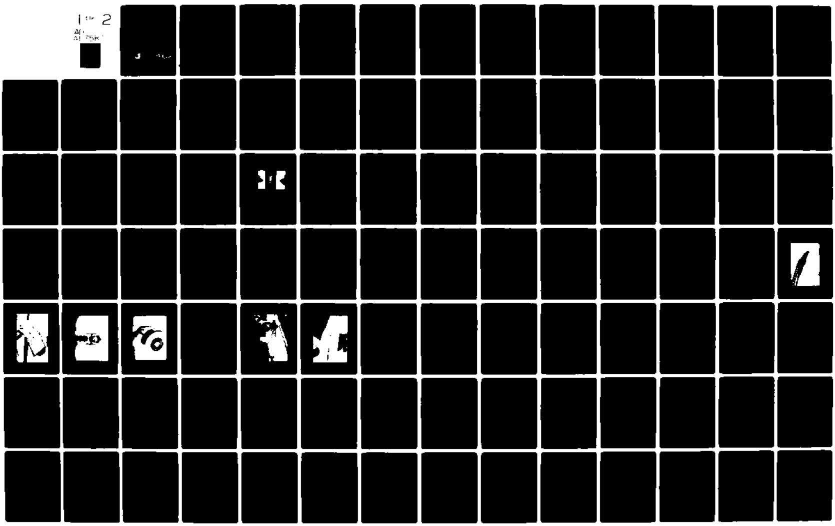

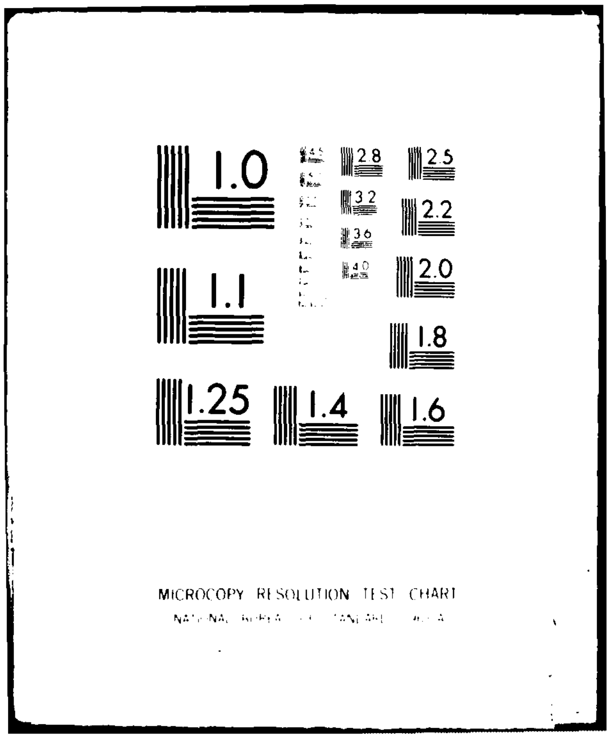
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THE STUDY OF FOREIGN OBJECT DAMAGE CAUSED BY AIRCRAFT OPERATIONS ON UNCONVENTIONAL AND BOMBDAMAGED AIRFIELD SURFACES

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JUNE 1981

FINAL REPORT
SEPTEMBER 1980 - JUNE 1981

AIR FORCE ENGINEERING AND SERVICES CENTER

AFESC

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This technical report documents the results of analyses conducted to assess the current level of technology available to determine the probability and extent of FOD to aircraft operating from unconventional and bomb-damaged airfield surfaces. The various mechanisms (i.e., jet blast, tire/ground interaction,...) which can create particles which can then cause damage and the level of susceptibility of various aircraft to damage are considered. Engine and airframe vulnerability to FOD is assessed and FOD prevention techniques

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currently being used are evaluated. The analysis concludes that the current level of technology only permits a qualitative understanding of FOD potential and identifies the information and data necessary to develop a quantitative relationship between debris characteristics and the extent of damage. In addition, a testing program is recommended to establish the quantitative relationship and to permit the development of a prediction methodology.

PREFACE

This report was prepared by The BDM Corporation, 7915 Jones Branch Drive, McLean, Virginia 22102, under contract number F08625-80-C-0206, for the Air Force Engineering and Services Center, Engineering and Services Laboratory, Tyndall Air Force Base, Florida 32403.

This report summarizes work done between September 1980 and June 1981. Captain Cary R. Wallington, USAF, was the project officer.

This report has been reviewed by the Public Affairs Office (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nationals.

This technical report has been reviewed and is approved for publication.

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Project Officer, AL&RS

JOHN E. GOIN, Lt Col, USAF
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Director, Engrg. and Services Lab

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SECTION I

INTRODUCTION

1. BACKGROUND

The Rapid Runway Repair Program being conducted by the Air Force Engineering and Services Center (AFESC) is seeking to develop new repair procedures, materials, and techniques, as well as alternative surfaces which will allow the rapid generation of sorties following an enemy attack. Several avenues of research in this program are impacted by considerations related to foreign object damage (FOD).

Current Air Force policy calls for the use of FOD covers over bomb craters that have been repaired using crushed stone. These covers are to preclude the incidence of damage to aircraft by the crushed stone. The FOD covers, however, are difficult to install, require maintenance and repair, and restrict access to the repaired surfaces. Elimination of FOD covers, or reduced requirements for their use, would assist in the overall effort to reduce the time associated with crater repair.

AFESC is also investigating the use of alternate launch and recovery surfaces for immediate aircraft operations following an attack. These alternative surfaces, such as stabilized soils and reinforced earth and gravel, may prove sufficiently strong to support limited aircraft operations, but may generate so much debris that FOD will result. A thorough understanding of the mechanisms by which various materials cause FOD is required in order to evaluate potential alternative surfaces.

The expectation is that damage to the runway and other facilities will leave a great deal of debris lying about. Since this may be combined with submunitions and other unexploded ordnance, the amount and degree that is required to be cleared is of considerable consequence. A determination of the mechanisms by which material may be ingested and what type of projectiles may damage aircraft and stores can assist in estimating the areas that must be cleared and the degree of cleanliness required for these cleared areas. The mechanisms may be such that objects far removed from the taxiways and minimum operating strip can still cause damage to aircraft. Also, the degree of cleanliness has obvious implications for the type of sweeping equipment required.

2. OBJECTIVE

The objective of this study was to assess the current level of technology available to determine the probability and extent of FOD to aircraft operating from unconventional surfaces and from bomb-damaged runways. The mission aircraft of interest included the F-4, F-15, F-16, F-111, A-10, C-130 and C-141, although the C-141 aircraft was not included in operations from unconventional surfaces.

The study was restricted to surface-induced FOD and excluded consideration of damage caused by bird strike, hail, ice and aircraft-related hardware and tools. FOD was defined as damage to the aircraft, its systems, or its stores caused by the impact or ingestion of objects orginating on the surface.

3. METHOD OF INVESTIGATION

The BDM Corporation (BDM), assisted by the University of Dayton Research Institute (UDRI), conducted a study to assess the current level of technology available to determine the probability and extent of FOD to aircraft operating from unconventional and bomb-damaged airfield surfaces. The study consisted of a technical literature search and contacts with various military commands, aircraft manufacturers, engine manufacturers, and other commercial and government research, development, and testing agencies. BDM or UDRI representatives visited several of these activities, including the airframe and engine manufacturers of the following mission aircraft: F-4, F-15, F-16, F-111, A-7, A-10, C-130 and C-141.

4. SUMMARY COMMENTS RELATING TO THE CONTENT

The primary emphasis in military and commercial aircraft operation is on FOD prevention. Air Force Regulation (AFR) 66-33 sets forth policy regarding FOD prevention and emphasizes the need to clean aircraft parking ramps, taxiways, and runways. The airlines, individually and collectively through the Air Transport Association of America (ATA), are also pursuing a vigorous FOD prevention program. As a result of these efforts, very few reportable FOD incidents are attributed to surface-induced FOD. An even fewer number identify pebbles, rocks, gravel, etc., as the cause, since most surface-induced FOD incidents are reported as having been caused by unknown objects. Thus, most operational experience and data have been accumulated on relatively clean surface conditions that are not representative of the surface conditions of interest to this study.

There is, however, a notable exception. There is significant experience accumulated by operators of Boeing 737 aircraft from unpaved runways, particularly gravel runways in Alaska. In anticipation of these requirements, the Boeing Commercial Airplane Company initiated a development program in 1965 leading to Federal Aviation Administration (FAA) certification of 727 and 737 aircraft for gravel runway operations. Boeing conducted a series of tests and observed the principal damage mechanisms to be:

a. Projection of gravel from landing gear tires, and

b. Ingestion of gravel resulting from engine inlet vortex.

Consequently, Boeing combined a number of aircraft modifications into a gravel runway configuration for the 737 that has permitted operations from gravel runways with FOD rates comparable to those experienced by

unmodified 737 aircraft operating from conventional runways. The modifications consist of:

a. Landing gear gravel deflectors,

b. Engine vortex dissipators,

c. Antenna protection,

d. Brake line shielding, and

e. Surface finish protection.

The observation of tests by Boeing indicated that debris lofted by landing gear tires constituted the most serious FOD threat. Boeing tests indicated that heavy debris impingement could be experienced in sectors 30 degrees horizontally and vertically from the tire, with random impingement at angles as large as 60 degrees. Depending on individual aircraft geometry, debris sprayed by the nose landing gear could be directly ingested by the engine or projected against external stores.

Ingestion resulting from engine inlet vortex formation is also considered by Boeing to be a significant contributor to engine FOD while operating on unprepared surfaces. Surface debris is disturbed by the rotational vortex flow and projected upward where it is entrained in the main inlet airflow and then ingested. In addition to the Boeing 737, vortex removal systems or dissipators have been installed in DC-8, F-18, F-111, and A-6 aircraft, but their use has been discontinued in all but the A-6 aircraft because of inconclusive evidence of their effectiveness.

The Naval Air Systems Command is another significant source of research. They were sufficiently concerned about the potential F-14 engine FOD threat posed by nosewheel spray to authorize the testing of a nosewheel deflector. The deflector, designed by the Naval Air Test Center, Patuxent River, MD, is being tested at the Landing Loads Track Facility at the NASA Langley Research Center, Hampton, VA. Tests of the F-14 nose landing gear will be conducted over known levels of debris at simulated taxi speeds. The spray pattern from the nosewheel tires will be determined with and without the nosewheel deflector installed.

Engine FOD resulting from the ingestion of debris is well understood qualitatively, but there do not appear to be any systematic tests using controlled pebble sizes that can be used to predict damage. One exception is the 1/4 inch gravel used in FAA tests. Operating policy normally requires the removal of engine components that are found to be damaged beyond established limits. Consequently, there is essentially no history of engines that have been continued in operation in a damaged state.

It is concluded that the current level of technology only permits a qualitative understanding of FOD potential. No quantitative relationship

has been established between debris characteristics and the extent of damage. Consequently, no quantitative prediction method is available. A testing program is needed to establish the quantitative relationship and to permit the development of a prediction methodology.

SECTION II

METHOD OF INVESTIGATION

The BDM Corporation, assisted by the University of Dayton Research Institute (UDRI), conducted the study in three phases:

- Data Collection,
- Data Review and Consolidation, and
- Data Analysis.

1. DATA COLLECTION

The data collection phase consisted of:

- Literature Search of BDM and UDRI Technical Libraries,
- Accession of the Defense Technical Information Center,
- Telephone Contacts with Government and Industry Activities, and
- Visits to Government and Industry Activities.

a. Telephone Contacts

Telephone contacts were made with representatives of government and industry activities in order to identify and locate sources of information and data relevant to the investigation. In some cases the information obtained by telephone indicated that a visit to the activity was not warranted. In several cases, however, it was evident that a subsequent visit to the activity would be necessary and desirable, and the telephone contacts were used to arrange those visits. Listings of the principal telephone contacts for government and industry activities are shown in Tables 1 and 2, respectively.

b. Visits

In preparation for visits to selected activities, BDM and UDRI prepared a checklist outlining the scope and type of information and data to be solicited. This list is shown in the references. These references were then used as a guide during interviews to focus the discussions on relevant material and provide consistency among visits. Visits were made to the government and industry activities shown in Tables 3 and 4, repectively, during the period September through November 1980.

TABLE 1. TELEPHONE CONTACTS WITH GOVERNMENT ACTIVITIES.

	ACTIVITY	CONTACT	BY
AIR FORCE			
	AERO PROPULSION LABORATORY	MR. A. MCKINNEY	UDRI
	AERONAUTICAL SYSTEMS DIVISION	LT. COL. D. ZIEG	UDRI
	FLIGHT DYNAMICS LABORATORY	MR. J. SPERRY	UDRI
	FLIGHT TEST CENTER	CAPT. HAGGARD	BDM
	FOREIGN TECHNOLOGY DIVISION	MR. R. GASTINEAU	UDRI
	INSPECTION AND SAFETY CENTER	MAJ. HUDSON	BDM
	OGDEN AIR LOGISTICS CENTER	MR. R. CLAY	BDM
	OKLAHOMA CITY AIR LOGISTICS CENTER	LT. COL. FREY	BDM
	SACRAMENTO AIR LOGISTICS CENTER	MR. BONNER	BDM
	TACTICAL AIR COMMAND	MAJ. G. PORTER	BDM
ARMY			
	AVIATION MATERIAL READINESS COMMAND	LT. COL. R. CHAPLIN	BDM
	SAFETY CENTER	LT. COL. M. ALVIS	BDM
NAVY			
	NAVAL AIR TEST CENTER	MR. G. RASPONI	BDM
	SAFETY CENTER	ABCS SISSELL	BDM
FAA			
	HEADQUARTERS	MR. E. GRAVES	BDM
	TECHNICAL CENTER	MR. R. JOHNSON	BDM
NASA			
	HEADQUARTERS	MR. A. R. TOBIASON	BDM
	LANGLEY RESEARCH CENTER	MR. T. YAGER	BDM
	LEWIS RESEARCH CENTER	MR. D. DANELS	BDM

TABLE 2. TELEPHONE CONTACTS WITH INDUSTRY ACTIVITIES.

ACTIVITY	CONTACT	BY
AIRCRAFT MANUFACTURERS		
BOEING COMMERCIAL AIRPLANE COMPANY	MR. J. TIMIDAISKI	BDM
DOUGLAS AIRCRAFT COMPANY	MR. P. FOSS	BDM
GD, FT. WORTH DIVISION	MR. C. PORCHER	BDM
GRUMMAN AEROSPACE CORPORATION	MR. C. SCHROEDER	BDM
FAIRCHILD REPUBLIC COMPANY	MR. J. TREVANY	BDM
LOCKHEED-GEORGIA COMPANY	MR. J. OSTERMAN	BDM
MCDONNELL AIRCRAFT COMPANY	MR. W. A. BATH	BDM
ROCKWELL INTERNATIONAL CORPORATION	MR. W. KURTZ	BDM
VOUGHT CORPORATION	MR. W. F. ADAIR	BDM
ENGINE MANUFACTURERS		
AIRESEARCH MANUFACTURING COMPANY	MR. J. JACK	UDRI
GENERAL ELECTRIC COMPANY	MR. R. G. STABRYLLA	UDRI
GM, DETROIT DIESEL ALLISON DIVISION	MR. R. FANNIN	UDRI
PRATT & WHITNEY AIRCRAFT GROUP	MR C. BROOKS	BDM
AIRLINES		
AMERICAN AIRLINES	MR. P. POWERS	BDM
EASTERN AIR LINES	MR. R. HORN	BDM
PAN AMERICAN WORLD AIRWAYS	MR. A. REINER	BDM
UNITED AIRLINES	MR. T. C. SCHWAN	BDM
ASSOCIATIONS		
AIR TRANSPORT ASSOCIATION	MR. J. T. MURPHY	BDM
AMERICAN INSTITUTE OF AERONAUTICS AND ASTRONAUTICS	MR. T. J. MESKEL	BDM

TABLE 3. VISITS TO GOVERNMENT ACTIVITIES.

	ACTIVITY	PERSONS	DATE	BY
AIR FORCE				
	AERO PROPULSION LABORATORY	MR. L. MCKINNEY	OCT 28	UDRI
		MR I. GERSHON	OCT 28	UDRI
	AERONAUTICAL SYSTEMS DIVISION	LT. COL. D. ZIEG	NOV 12	UDRI
		MR. T. KING	NOV 12	UDRI
	FLIGHT DYNAMICS LABORATORY	MR. J. SPERRY	OCT 17	UDRI
		MR. D. SHEETS	NOV 4	UDRI
	INSPECTION AND SAFETY CENTER	MAJ. HUDSON	SEP 26	BDM
		MAJ. SEYMOUR	SEP 26	BDM
	TACTICAL AIR COMMAND	LT. COL WILSON	OCT 16	BDM
		MAJ. G. PORTER	OCT 16	BDM
		CMS GILLESPIE	OCT 16	BDM
NAVY				
	NAVAL AIR TEST CENTER	MR. G. RASPONI	OCT 23	BDM
		MR. S. CHASEN	OCT 23	BDM
	SAFETY CENTER	CAPT. S. P. DUNLAP	OCT 17	BDM
FAA				
	HEADQUARTERS	MR. E. GRAVES	OCT 8	BDM
NASA				
	HEADQUARTERS	MR. A. R. TOBIASON	NOV 10	BDM
	LANGLEY RESEARCH CENTER	MR. T. YAGER	OCT 17	BDM
		MR. W. VOGLER	OCT 17	BDM

TABLE 4. VISITS TO INDUSTRY ACTIVITIES.

ACTIVITY	PERSONS	DATE	BY
AIRCRAFT MANUFACTURERS			
BOEING COMMERCIAL AIRPLANE COMPANY	MR. E. LUND	SEP 24	BDM
	MR. R. RANDALL	SEP 24	BDM
	MR. M. TIEDE	SEP 24	BDM
GD, FT. WORTH DIVISION	MR. C. PORCHER	SEP 23	BDM
	MR. F. G. WATT	SEP 23	BDM
GRUMMAN AEROSPACE CORPORATION	MR. H. LEUTHER	NOV 25	BDM
	MR. L. OLESON	NOV 25	BDM
FAIRCHILD REPUBLIC COMPANY	MR. G. SHAW	NOV 25	BDM
	MR. J. BARBERA	NOV 25	BDM
	MR. R. URAVITCH	NOV 25	BDM
LOCKHEED-GEORGIA COMPANY	MR. J. OSTERMAN	NOV 4	BDM
	MR. R. BROWN	NOV 4	BDM
	MR. B. M. CRENSHAW	NOV 4	BDM
	MR. C. BUSH	NOV 4	BDM
MCDONNELL AIRCRAFT COMPANY	MR. W. A. BATH	SEP 22	BDM
	MR. D. J. THOMPSON	SEP 22	BDM
	MR. T. MIKOLS	SEP 22	BDM
	MR. D. HOLLWEGER	SEP 22	BDM
VOUGHT CORPORATION	MR. W. F. ADAIR	SEP 23	BDM
	MR. T. C. BILLINGS	SEP 23	BDM
ENGINE MANUFACTURERS			
GM, DETROIT DIESEL ALLISON DIVISION	MR. R. FANNON	NOV 3	UDRI
	MR. G. BICHONNIA	NOV 3	UDRI
	MR. K. O'CONNER	NOV 3	UDRI
PRATT & WHITNEY AIRCRAFT GROUP	MR. T. P. DARCY	NOV 3	BDM
	MR. C. BROOKS	NOV 3	BDM

2. DATA REVIEW AND CONSOLIDATION

The data and information obtained were reviewed and then consolidated into the following areas:

- FOD Characteristics,
- Damage Potential of Mission Aircraft,
- Runway Surface and Environmental Conditions,
- Techniques for Predicting FOD,
- Acceptable FOD Levels, and
- FOD Prevention Techniques.

3. DATA ANALYSIS

The consolidated data and information were analyzed to assess the ability of the current level of technology for predicting the probability and extent of FOD to aircraft when operating from other than smooth concrete runways.

Due to the general lack of quantitative data, the research analysis has had to develop and include selected preliminary first order quantification to bound the problem. These efforts, while not originally anticipated, were felt necessary for completeness, but do not in any way constitute the analytic treatment that the subject requires in order to provide design information.

There is a major methodological dilemma associated with the presentation of data for this report. This problem is based on the fact that most of the information collected as basic data is in the form of essentially undocumented, qualitative statements (the term oral history is used to characterize this type of data by researchers in the field). As such, this data is somewhat subjective by definition. This leads to an issue concerning the degree to which BDM's analysis and judgement should be mixed with the basic data.

This has led to the following organization. The collected material is presented with little additional comment, critique, and analysis so that the available data is portrayed in as near to the original form as possible. Critique and analysis is then presented in the following sections. It is hoped that this method will allow the most accurate view of the data and clearly separate BDM's judgment and analysis of the data base from those given to BDM by "experts."

SECTION III

PRESENTATION OF DATA

1. INTRODUCTION

a. Definition of FOD

Air Force Regulation (AFR) 66-33, Prevention of Foreign Object Damage (FOD) to Aircraft, Missiles or Drones, defines FOD as damage to, or malfunction of, an aircraft, missile or drone caused by an object that is alien to an area or system, being ingested by, or lodged in a mechanism. AFR 66-33 states that FOD may cause material damage or it may make the system or equipment unusable, unsafe, or less efficient.

b. Scope Limitations

This study was concerned with damage to the aircraft, its systems or its stores caused by the impact or ingestion of objects originating on the surface. Damage caused by bird strikes, hail, and ice were specifically excluded, as well as aircraft-related hardware and tools. Since the study involved a combat scenario, primary consideration was given to damage that would result in a mission abort. Long-term system degradation, such as engine blade erosion that might result from ingestion of dust or sand, was a secondary consideration.

c. Potential Object Characteristics

Because of the thrust of the study, the objects of principal interest could be pieces of material such as dirt, concrete and asphalt. These pieces could range in size from dust-like particles up to particles with typical dimensions of inches. (It is assumed that very large pieces of cement would have either been removed or would not be subject to forces sufficient to dislodge them.) Metal particles from nearby damage or bomb fragments could also be present. These fragments could be composed of a variety of metal types (e.g., aluminum, steel) and weigh up to one-half pound. When influenced by forces which could produce FOD, the objects could be lying stationary on the surface, or may be airborne and travel several hundred feet per second (the speed likely for a piece of airborne debris caused by exhaust).

2. MECHANISMS WHICH CAN CREATE PARTICLES WHICH CAN THEN CAUSE FOD

a. Jet or Propeller Blast

A serious threat to all mission aircraft is debris that is created by the airflow from jet engine exhausts or propeller slipstreams. To give some indication of this problem, the jet exhaust velocity profiles which emanate from the F-15 aircraft are shown in Figure 1. The profiles

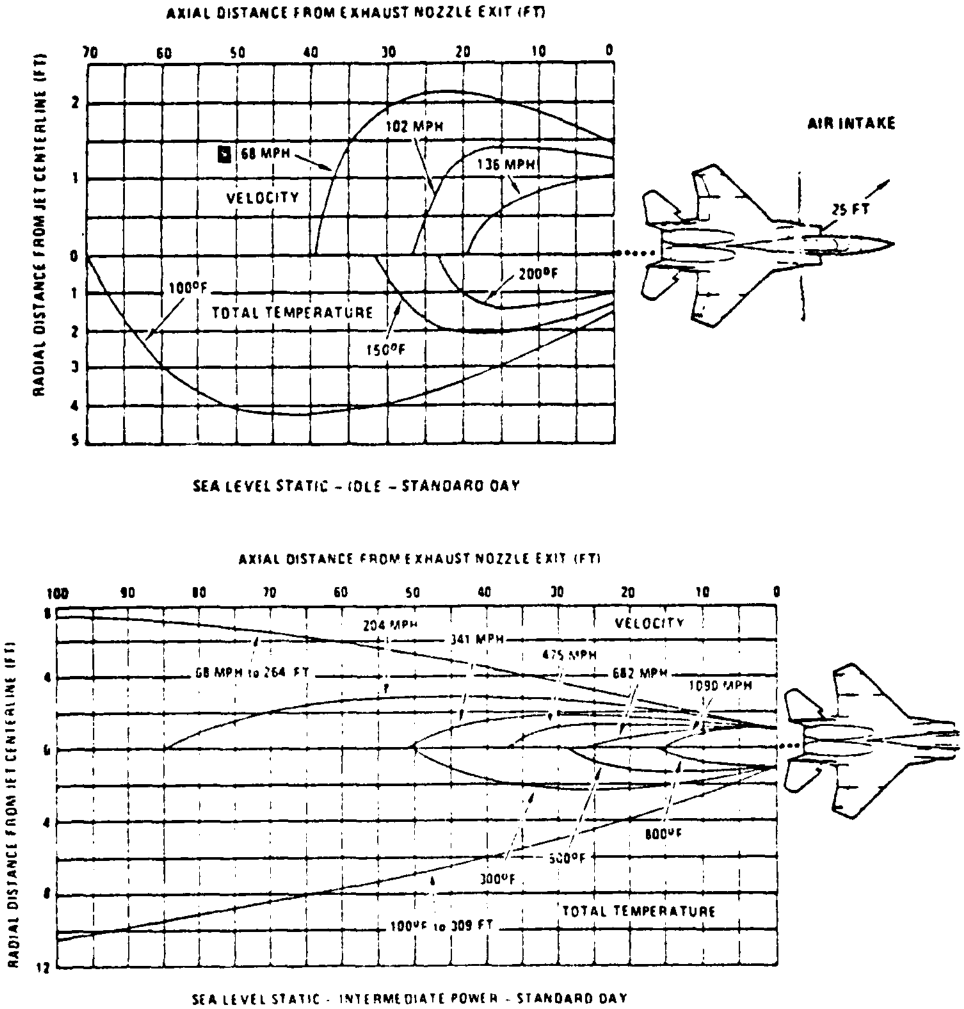


Figure 1. Jet Exhaust Velocity Profiles Emanating from F-15 Aircraft.

are shown in the horizontal plane for both idle and intermediate (non-afterburning) power settings. These power settings are the conditions which might be found during taxiing operations. Except for the boundry layer (small in height, fractions of an inch high) which forms on the surface, the profiles in the vertical plane are approximated by a 90 degree rotation of the horizontal profiles around the aircraft engine centerline.

The generation of the trajectory of debris is not easily determined by analytical methods, but some sizing calculations will indicate the potential. The phenomena is complicated by the irregular sizes of the debris. The jet blast will initially cause sliding of the object over the surface based on the velocities in the boundary layer and the drag between the irregular object and the surface (which could be grass, concrete, or asphalt). Due to the irregular shape, forces could be produced which would lift the particle into the air. At this time the mass, center of gravity, and aerodynamic forces will determine the trajectory.

In addition, particles can be scoured from the surface by the combination of high velocities and the temperatures of the exhaust or propeller slipstream. No complete theoretical treatment of these phemonena has been found.

As an indication of the forces which could act on particles, two examples are cited based on particles from real explosions. Following tests using live explosives, a piece of concrete with dimensions approximately 1-1/2 inch by 1/2 inch by 7/8 inch weighing about one-half ounce was found among the debris. Most irregular objects have a drag coefficient of about 1.0 (see FLUID DYNAMIC DRAG by Hoerner). The air velocity for which the weight equals the drag forces is shown in Table 5. Also shown is the velocity to cause sliding over a smooth surface. For sliding, the Handbook of Chemistry and Physics (46th edition of The Chemical Rubber Co., 1964, 1965) gives a coefficient of friction of steel on steel of .58, wood on brick of .6 and polymethyl methacrylate on steel of .4 to .5. Therefore, a coefficient of friction for the sample used in these tests is judged to be about one-half.

In another test, a piece of bomb fragment left exposed on the surface measured 2-1/2 inches by 1/4 inch by 1/2-inch and weighed about one ounce. The velocities which will lift (weight equal to drag) and slide this piece are also shown in Table 5. As later data will indicate, this piece will likely cause damage if it is ingested into an engine.

As the data in the table indicates, the exhaust velocities which exist at the fighter aircraft tailpipes are sufficient to move the large example pieces. Moreover, these velocities exist at long distances behind the exhaust. In general, compared to larger particles, smaller particles have aerodynamic forces which are larger in proportion to their weight. An

TABLE 5. VELOCITY TO MOVE PARTICLE.

PARTICLE	WEIGHT EQUAL AERODYNAMIC FORCE	SLIDE OVER GROUND COEFFICIENT OF FRICTION = 0.5
LARGE STEEL FRAGMENT	68 (46)	68 (46)
CONCRETE	56 (38)	50 (34)

Note:

1. (Velocities In Feet Per Second And Miles Per Hour)
2. Velocity Differences Due To Dimensions Assumed When On The Ground And In Free Air.)

understanding of this can be made by considering several factors. First, the normal expression for aerodynamic forces is (for example, drag):

$$D = 1/2\, \rho\, V^2\, S\, C_D$$

where:

- D = drag force in pounds, which acts in the direction of the velocity of the airstream
- ρ = density of the air (slugs/ft^3)
- V = free stream air velocity in feet per second
- S = reference area in which the drag coefficient is based in square feet. (Note: In the case of a rock, the area would be the cross sectional area)
- C_D = nondimensional drag coefficient.

Second, the weight of an object (W) can be expressed as the product of its density and volume. The volume can be related to some characteristic dimension in most regularly shaped objects. Third, to move the object, the forces are expressed as $D = \frac{W}{g}a$, where g is the acceleration due to gravity and a is the object acceleration.

Based on this information, the relation between the aerodynamic forces and the weight can be expressed as:

$$\frac{\text{Aerodynamic Forces}}{\text{Weight}} = \frac{1/2 \text{ Air Density} \times (\text{Velocity})^2 \times \text{Constant} \times (\text{Length})^2}{\text{Particle Density} \times (\text{Length})^3}$$

Therefore, this ratio decreases as length (or size) increases. Hence for larger particles, the aerodynamic forces are lower than inertial forces, and the smaller pieces will be more subject to movements by exhausts than will large objects.

b. Debris Lofting by Tires

(1) General

Very little is known either qualitatively or quantitatively about how tires loft loose material over which they run. The materials of specific interest to this study are stones, pieces of metal shrapnel, hard agglomerations of soil, and dust. All of these materials may be expected to be present on the surfaces of repaired paved runways and alternate runways. The principal material currently used for making rapid repairs of runway damage is crushed limestone. The limestone is held in place by compaction and/or physical restraints such as meshes and mats. Continued over-rolling of crushed limestone surfaces loosens the stones. Thus, a runway surface repaired by using crushed limestone, and subjected to heavy

aircraft traffic, may be expected to consist of a mixture of compacted material, loose debris, and dust. This would also be true for any runway or taxiway surface which was comprised of crushed stone.

Studies conducted by the Boeing Corporation (1) Boeing Commercial Airplane Co., Airplane Requirements for Operations on Gravel Runways, D6-45222-1, March 10, 1980 and 2) Boeing Commercial Airplane Divisions, Substantiation for 727 Gravel Runway Operation, D6-18498, October 11, 1966) supporting use of Boeing 727 and 737 commercial aircraft from unpaved runways indicate strongly that macrodebris (chunks with chracteristic dimensions greater than 10 mm) is projected by aircraft tires in relatively intense fields extending 30 degrees on each side of the tire plane and 30 degrees up from the runway surface. Less intense concentration of debris is projected at angles between 30 and 60 degrees. Photographs of aircraft traveling through standing water show strikingly similar behavior of the spray produced by the tire action. These results indicate strongly that materials lofted by the nosewheel of an aircraft can impact most of the underside of the fuselage, plus the engine air intake ducts on aircraft where these ducts are located well to the rear of the nosewheel. Thus, all types of aircraft may be expected to be struck by runway debris along much of the bottom of their fuselages and wings, and engines will certainly ingest debris.

Except for debris that is projected by other aircraft, the principal means by which foreign objects occur is the interaction of an aircraft tire with the debris or surface. The debris can cut or otherwise damage the tire so that a takeoff would be hazardous. Occasionally, the tire tread separates from the tire and becomes a foreign object.

(2) Tire Damage

Boeing reported (Reference 5) that tire wear for 737 aircraft operating on gravel runways is generally increased and can be as much as four times that of 737 aircraft operating on conventional runways. The Tactical Air Command has experienced an increase in the number of cut tires at bases where debris is encountered. Airlines have also reported an increased frequency of cut tires at those locations where operating surfaces have deteriorated. This damage to tires can cause pieces of tire tread to be present on surfaces.

(3) Tire Spray

Boeing tests on gravel runways showed that aircraft tires sprayed rocks in heavy concentrations in sectors 30 degrees horizontally and vertically from any of the tires, with random impingements at angles as large as 60 degrees (see discussion in Appendix D and G). Rocks that were momentarily lodged in the tire grooves, however, could be projected vertically at angles exceeding 60 degrees. Boeing also noted that spray concentrations were particularly heavy during tire spinup at landing touchdown. They also reported that the velocity of the objects in the

spray was characteristically comparable to the aircraft velocity. Although not measured, the velocity could be even greater due to relief of tread compression as the rocks were released.

Spray from the nosewheel tire is of great concern since its pattern envelops many of the potentially vulnerable areas of an aircraft, particularly the engine inlets of some aircraft. Additionally, during aircraft turning operations, the nosewheel will be steered or will swivel so that the spray pattern can be directed outboard of its normal location.

(4) Debris Lofting by Tire Treads

Four mechanisms have been tentatively identified as being responsible for lofting both dust and macrodebris: "tread envelopment," "pinch lofting," "tread gripping," and "drag acceleration by lofted water." Tread envelopment is produced by the loaded tire tread deflecting around a pellet over which it rolls. The tread is strained in the plane of the runway surface by the load placed upon it and this strain is relieved rapidly as the tread clears the runway surface at the rear edge of the footprint. The release of the tread strain launches enveloped runway material at velocities which may exceed the aircraft roll velocity by a considerable margin. Clearly, the likelihood of lofting macrodebris from runways and the launch velocities is affected by the tire tread straining in and near the footprint. Because these strains are increased significantly during breaking and turning, so both of these maneuvers are expected to increase the amount and severity of tire-launched debris. The angle above the runway plane at which the material is released is largely dependent upon the angle between the tread surface and the runway adjacent to the rear of the footprint, and the time between tread clearance and particle launch. A separate factor which may increase the final projection angle of lofted pellets is subsequent impacting of the launched pellets with other pieces of runway material. Projection of material at high speed contributes both to impact damage and to the length of time airborne in ballistic flight.

A modification of the tire envelopment mechanism is probably responsible for much of the dust lofted by a moving aircraft. The dust must simply be broken free from the runway surface by scouring from the over-rolling tires, raised slightly, and swept up by strong air currents accompanying aircraft operation. This material may be elevated to a considerable altitude and remain airborne for some time.

Consideration of the tire envelopment concept for launching runway debris would indicate that the trajectories of the vast majority of launched material should remain very near the plane of the tire, although these trajectories may be distributed in angles above the runway surface. A modification of the envelopment concept where objects on the runway are partially covered by the edges of the tire footprint (pinch lofting) leads to predictions of materials being lofted with trajectories at large angles to the tire plane. Downward pressure on part of the upper surface of an

object on a runway produces relatively violent forces with components directed perpendicular to the tire plane. At the same time, these particles are enveloped and receive a rearward velocity component due to stress relaxation in the tire tread near the rear of the footprint. These two velocity components combine to produce resultant vectors at relatively steep angles to the tire plane.

The tread-gripping mode for lofting runway debris involves the circumferential grooves in tire treads gripping individual debris pellets as they are over-rolled and holding them for some time after the rotative tread has cleared the rear of the footprint. Particles are subsequently released, due to centrifical force of the whirling tire, and are projected tangentially away from the tread surface. Debris launched by tread-gripping must be confined to nearly the plane of the tire but the angle off the runway surface may have any value. The velocity of pebble launching will almost always coincide closely with tread velocity (also the forward velocity of the aircraft). The tread-gripping mechanism can be effective only when tires with lateral tread grooves are employed (tires with such tread grooves are becoming progressively more popular at the moment) and it can be responsible for launching only pebbles that fit the grooves, i.e., have at least one dimension comparable to the groove width. The debris dimension factor probably renders tread gripping relatively unimportant with regard to the total mass of material lofted by aircraft tires. The mechanism may be important in one respect, however, since it can readily produce impacts in the wheel wells where aircraft could be vulnerable.

Aircraft tires running through standing water loft this water by hydrodynamic displacement. The rapid acceleration of the water and its high flow velocities can entrain and loft finely divided debris at some velocity. This phenomenon has not been identified separately as a pellet-loft mechanism but theoretical considerations indicate that the effect should be present. Like tread-gripping, this phenomenon probably cannot produce serious dust-lofting problems.

A final source of lofted macroparticles is debonding and breakup of tire treads. Although the material launched is not found originally on the runway, the severity of this problem is directly affected by runway conditions. Tire tread breakup is caused by the growth of incipient flaws in the tire tread, which cannot be detected by simple visual inspection until the damage level is nearly catastrophic. This type of damage occurs in nearly all aircraft tires, but is accelerated greatly when the tire tread is subjected to shocks produced by overrolling rock surfaces. The size of the fragments projected varies from chunks whose characteristic dimensions are the tread thickness to large segments of the entire tread. They are generally launched in proximity to the plane of the tire, but any launch angle with respect to the runway surface is nearly as probable as any other. Tire tread material from the nosewheel may strike the under surface of the fuselage. Wing wheel material may strike the

under surface of the wing and the wheel wells. Those materials, however, are generally confined to the plane of the wheel.

c. Inlet Vortex

The NASA Lewis Flight Propulsion Laboratory, now the NASA Lewis Research Center, reported in Reference 1 that a vortex is formed between a jet engine inlet and the ground surface under certain conditions.

The vortex phenomena occurs at the beginning of takeoff roll and during taxi and static conditions. A slight cross wind helps the vortex to occur but the phenomena is not present in high winds or at aircraft speeds greater than approximately 20 knots. Surface debris can be disturbed by the vortex flow and projected upward where it is then entrained in the main inlet flow and subsequently ingested. It was stated that pebbles lodged in surface cracks can be more readily picked up than those exposed on a smooth surface.

Reference 2 indicates that the materials which were sucked up by the inlet with the blowaway jet inactive consisted of pebbles as large as 3/4 of an inch in diameter, large aircraft-type rivets up to 1/4 inch shank and 1-1/2 inches long, various washers up to 1-1/2 inches in diameter, sheet metal strips up to 6 inches long and .020 inches thick, or metal clips and other metallic parts. To explore whether free-rolling materials could be sucked up, 1/2-inch marbles were distributed below the inlet. It was found that these also could be sucked up by the inlet. Rags could also be sucked by the inlet, but usually they were sufficiently light to be blown away by the periphery of the vortex. It appeared that, to be readily picked up, a material should be neither too heavy nor too light.

Sucking up of anything by the inlet was a comparatively rare event. When a considerable amount of debris was deliberately scattered beneath the inlet, it often took 1 or 2 minutes for something to be sucked up. No shower of items proceeded into the inlet at any time. Although a full scale test will pick up more items per unit time than a model, even at full scale one would not expect a shower of items to enter an inlet. From time to time, however, one could expect material to be aspirated, depending on weather conditions, runway cleanliness, and other aircraft slipstreams creating vorticity.

3. SUSCEPTIBILITY OF AIRCRAFT TO DAMAGE

a. General

Turbojet and turbofan engines are the most vulnerable aircraft components to FOD. The objects can be ingested by the engine as a result of tire spray or engine inlet vortex formation. Once ingested the objects can readily cause sufficient damage to abort a mission. Military Specification MIL-E-5007D, General Specification for Aircraft Turbojet and Turbofan Engines, establishes quantitative requirements for engine

ingestion of birds, sand, water, and ice. However, with respect to the ingestion of other foreign objects, it states only that the engine shall operate for two inspection periods following damage with a minimum stress concentration factor of three to fan and compressor blades and stators. It does not address the type, size, weight or velocity of the foreign objects causing the damage. Appendix B describes some engine design parameters which influence susceptibility to FOD.

b. Engine Vulnerability

Some of the data acquired during this effort can be used to support a preliminary assessment of the effects of pebble ingestion on jet aircraft engines. In this section, the pertinent results are summarized and evaluated.

Foreign object damage (FOD) in aircraft has been a subject of intensive investigation for many years. Generally FOD can be divided into two categories, soft body and hard body. Soft body refers to bird strike. Hard body refers to ice, stones, and metal objects. The FAA distinguishes two types of FOD, Group I and Group II (Table 6). Group I events only affect a single engine, so shutdown is an allowable response. Group II threats affect all engines, so operation at a minimum power level must be maintained.

The vast majority of the FOD literature refers to soft body FOD. Since many of the past studies have been motivated by a desire to develop lighter fan blades, special emphasis has been placed on advanced composite materials. Loading mechanisms for soft body FOD on these engine parts are fairly well understood.

Much less work has been done on hard body FOD. Damage mechanisms are usually nicks and dents in leading edges. This type of damage introduces an effective crack that may propagate due to cyclic loading of the blade. Eventually the blade will break. Loss of a single blade is not catastrophic for an engine. In many cases, however, a blade will destroy an engine as it travels back through the compressor stages. For example, the manufacturer judged the loss of a first stage fan or a fourth stage compressor blade in a F-100 engine to be generally catastrophic, while loss of seventh stage blades was not.

The FAA requires a hard body FOD acceptance test which includes an aircraft tire tread, 1/4 inch gravel, sand, and ice. Table 6 shows the FAA requirements. Figure 2 illustrates typical hard body FOD damage on a simulated compressor blade leading edge. Appendices E and F present pertinent excerpts from specifications relative to engines.

There are a number of anecdotal accounts of the catastrophic consequences of an ingestion of small steel objects by jet engines. According to verbal statements made during visits, apparently objects as small as

TABLE 6. FAA HARD BODY FOD REQUIREMENTS, FROM CIRCULAR AC 33-1B.

GROUP I OBJECTS:	Engine must not explode, disintegrate, or start an uncontrollable fire. Safe shutdown must be demonstrated. Mechanics hand tool Typical steel bolt and nut Aircraft tire tread
GROUP II OBJECTS:	Engine must continue safe operation without flameout or significant sustained power loss. Power recovery must be at least 75 percent. *GRAVEL (1/4-INCH DIAMETER) *SAND *ICE (INLET DUCT AND LIP FORMATIONS) *HAIL (1 AND 2-INCH DIAMETER)

* AMOUNTS VARY WITH ENGINE INLET SIZE.

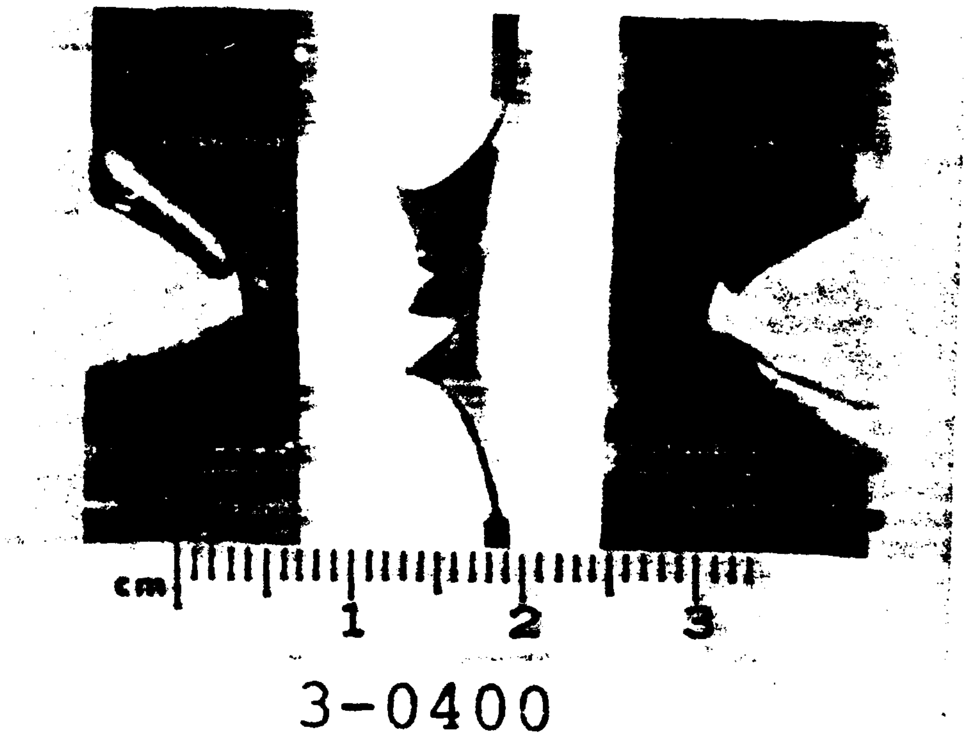


Figure 2. Typical Hard Body FOD on Simulated Compressor Blade. (Steel Ball, 6.4 mm Diameter, 1 gram/15 grain 883 ft/sec Against 0.5 mm 8-1-1 Titanium). (From Reference 8)

1/4 inch bolts can be lethal. It would appear that any steel object larger than about 20 g can cause immediate catastrophic failure.

FOD effects in turbojets and fanjets differ. Fanjets are primarily threatened by soft objects and turbojets by hard objects. The reason is that the first stage fan of fanjets is normally very tough and capable of breaking up some objects. Also, foreign objects can be thrown radially outward by the encounter with the fan and hence do not necessarily impact the later compressor blades. Most engines being developed now are fanjets. The J-79 that powers the USAF versions of the F-4C, D, E, however, is a turbojet.

There do not appear to have been any systematic tests of controlled pebble sizes that can be used to predict damage. The only exception is the 1/4 inch gravel used in FAA tests. This gravel does not appear to damage metal fan blades, although it is reported to be lethal to composite fan blades.

While there are field reports of damage caused by hard-body FOD, there is seldom information describing the object. It was verbally reported, however, that the F-100 engine is suspected of frequently ingesting titanium shards which are discarded from the engine. These weigh 7 g and apparently do not produce serious damage in the engines.

Rocks and steel projectiles behave differently in FOD encounters. The difference is apparently traceable to impact strength. Rocks can be pulverized by impact with first stage fan blades. They then flow almost like a fluid with a size probably characteristic of the constitutive mineral grains. Steel, on the other hand, is not broken by the fan blades and passes intact into the compressor blades. The compressor blades are extremely thin and are subjected to severe cyclic loading. Any macroscopic damage will quickly lead to structural failure of the blade. Unfortunately, few documented encounters of rocks with engines exist. What evidence there is suggests that rocks can dent or nick fan blades, but the debris from the first fan blade does not seriously damage compressor blades.

There were numerous accounts of dust ingestion by engines. Engines must pass dust ingestion tests prior to acceptance. However, when aircraft are operated in environments where a great deal of soil is lofted, engine life is often degraded. These reported degradations do not impact on the limits of this study. Unfortunately, the nature of lofted earth material in situations causing engine failure has not been reported.

(1) Sand and Dust

MIL-E-5007D specifies that an engine shall operate satisfactorily throughout its operating range at ground environmental conditions with air containing sand and dust in concentrations up to 3.3×10^{-6} pounds of sand per cubic foot of air. It further states that the engine and its

components shall be capable of operating at maximum continuous thrust with the specified concentration of sand and dust for a total period of 10 hours with not greater than 5 percent loss in thrust, 5 percent gain in specific fuel consumption, and no impairment of capability to execute thrust transients. (The appropriate parts of MIL-E-5007D are reproduced in Appendix F.) The specified sand contaminant shall consist of crushed quartz with the total particle size distribution as follows:

Particle Size, Microns	Quantity, Percent by Weight Finer than Size Indicated
1,000	100
900	98-99
600	93-97
400	82-86
200	46-50
125	18-22
75	3-7

An engine designed to satisfy this specification should not be damaged sufficiently by the ingestion of sand to cause a mission abort. Long-term blade erosion should be expected, however.

(2) Gravel

MIL-E-5007D does not establish quantitative requirements for gravel ingestion, and no systematic testing is performed. The FAA, however, does require tests involving ingestion of 1/4 inch diameter gravel for engines used in commercial aircraft (see Appendix E). FAA Circular AC 33-1B states that an engine must continue safe operation without flameout or significant power loss following ingestion of a specified amount (dependent on inlet area) of 1/4 inch diameter gravel. This size gravel does not appear to cause significant damage. However, larger size gravel, even though it generally disintegrates on contact with a fan blade or compressor blade, can cause significant damage.

(3) Metallic Objects

MIL-E-5007D does not establish requirements for ingestion of metallic objects. On the other hand, although FAA Circular AC 33-1B does not require continued engine operation, there is a requirement that an engine not explode or disintegrate following ingestion of a mechanics hand tool or a typical steel nut and bolt. A metallic object, such as a bomb fragment, does not disintegrate on contact with a fan blade or compressor blade and subsequently causes substantial damage to following stages. Typical metallic object damage to a simulated compressor blade was shown in Figure 2. The damaged blades frequently break and cause additional damage.

The evidence shown in Figure 3 shows that damage from a 1 gram particle of steel may cause catastrophic damage to an engine. As

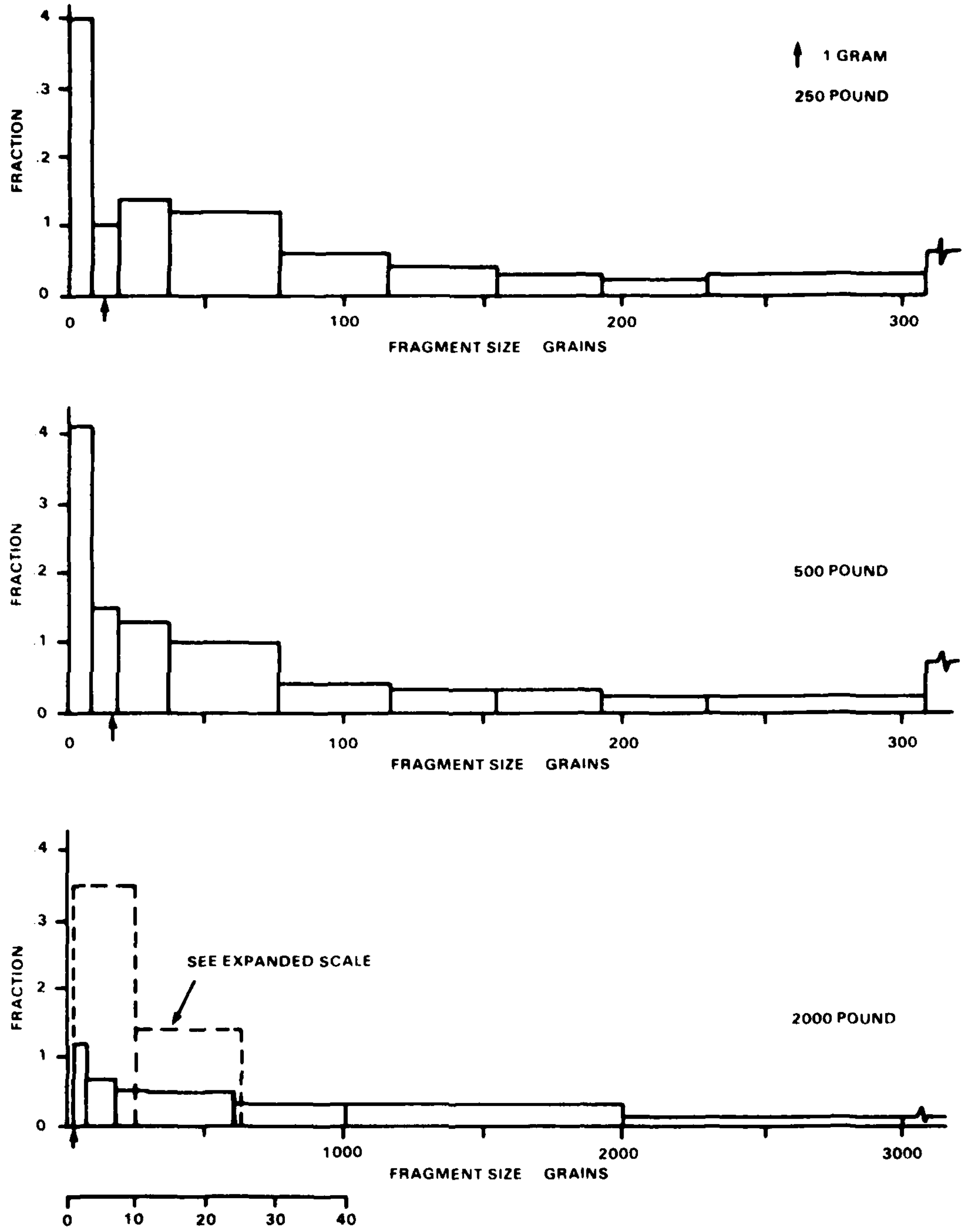


Figure 3. Fragment Distribution of General-Purpose Bombs.

can be seen from Figure 3 more than 40 percent of all bomb fragments are larger than this size. Hence almost half of the bomb fragments are larger than a size which, if ingested, could cause damage to an engine. Objects larger than 20 grams (300 grains) comprise about 6 percent of the fragments from small general purpose bombs and as much as 13 percent for general purpose bombs in the 2000 lb class. These larger fragments (greater than 300 grains) would probably cause damage, since they are about the size of smaller compressors and turbine rotor blades or the small size aircraft steel bolt Table 6, Group I, e.g., to cause immediate engine shutdown by the FAA. Hence, there is little doubt that the ingestion of some of the larger bomb fragments could result in mission abort.

4. DEBRIS IMPACT AGAINST AIRFRAMES

By far, the largest amount of runway debris expected to strike combat aircraft operating from repaired or alternate runways is derived from the plane's own wheels interacting with the runway surface. Some airfield operating modes may also expose aircraft to occasional impacts from material lofted by other aircraft, since particles launched during a takeoff or landing could strike a following aircraft. This material from other aircraft can, in principle, strike the side and upper surfaces of the aircraft from any angle. However, such impacts will occur principally on the forward facing portions of the airframe and can produce damage when they strike such various surfaces as airframe, a cockpit transparency, or a radome.

In order to understand the damage potential, an estimate was made to determine how airframes can be damaged by projectiles from their own tires. This was accomplished by estimating impact conditions that lead to perforation of the skin on the underside of the airframe. More benign impacts may batter the airframe and eventually cause serious structural damage, but failures within 2 to 3 missions will only be produced by skin perforation and associated damage to vital components. It should be noted that there are impacts inside the wheel wells where a variety of components with different ballistic damage thresholds are exposed. This must be tested separately.

Perforation of aircraft skins by projected stoney material can be investigated with a straight-forward ballistic testing program in which a variety of stone sizes and shapes is launched against aircraft skin configurations to determine ballistic-limit impact conditions. Such data are currently unavailable.

An attempt was made to generally size the problem. The estimate attempted to anticipate the results of ballistic tests by using an empirical penetration equation developed for studying the penetration of airframes by fragmentation weapons. It should be cautioned that empirical equations do not have good reputations for predicting ballistic results beyond the ranges of parameters covered by the data from which they were generated. The particular equation chosen was developed for predicting

perforations of aircraft skins by relatively rigid penetrators made from medium to high density metal (ρ > 7.8 g/cc) and traveling at relatively high velocities (velocities greater than a few hundred meters per second). It has been extracted from the most recent joint-service handbook on penetration mechanics (Reference 17). The impact situations considered here have both similarities and differences with respect to those for which the equation was developed. The target materials are within the range of those considered. It is anticipated that all of the potential dangerous debris lofted from the runway will remain rigid during impact, but that the density of most of this debris is typical of stoney material (ρ = 2 to 3 g/cc). Impact velocities are limited to somewhat greater than takeoff velocities for the aircraft in question which are considerbly lower than typical fragment impact velocities.

The chosen empirical relationship is presented in the following equations 1 through 4.

$$V_{50} = C_{bf}\left[\frac{\rho_f T A_p}{W}\right]^{b_f}\left[\frac{\rho_f T A_p}{W_o}\right]^{f} \sec^h\Theta \qquad 1$$

$$A_p = \frac{d^2}{\sqrt{2}} \quad (1 + \pi/4) \qquad 2$$

$$\rho_f = \frac{m_f g}{f_f} \qquad 3$$

$$W_o = 6.49 \text{ gm } (100 \text{ grains}) \qquad 4$$

$$V_{50} = \left[\frac{C_{bf}}{\cos^h\Theta} 2.41 \frac{T}{d_f}\right]^{b_f}\left[\frac{1.26\ \bar{\rho}_f\ \ T d_f^{\ 2}}{m_o}\right]^{f} \qquad 5$$

The term C_{bf} in equation 1 is a characteristic impact velocity which is dependent upon the target material: ρ_f is the weight density of the impinging fragment; T is the target thickness; A_p is an equivalent presented area of the projectile defined in equation 2; W is the weight of the projectile; W_o is the weight of a reference projectile; and Θ is the angle between the trajectory of the incoming projectile and the normal to the target surface. The terms b_f, f, and h are empirically derived constants. The term, d, in equation 2 is the equivalent dimension of the projectile; m_f in equation 3 is the mass of the incoming fragment; V_f is the fragment volume; and g is the local acceleration of gravity.

The formulation of the equation has been simplified by considering the incoming projectile to be a sphere, and evaluating and combining various definitions of subterms. Results appear in equation 5. The term, d_f in

equation 5 is the diameter of the projectile; ρ_f is the mass density of the fragment material and m_o is the mass of the reference fragment.

Equation 5 is used to evaluate the ballistic limit for perforating the underside of a typical airframe with spherical limestone pebbles. Pebbles were assumed to be spherical for application of this equation, since the development treats projectile shape only by differentiating between "extended" and "chunky" fragments. A "chunky" fragment is one with all linear dimension comparable. It is assumed that the aircraft skin is made from 2024-T3 aluminum 1.5 mm thick. The stones are assumed to be limestone with a mass density of 2.5 g/cm^3. The values for the empirically derived constants of equation 5 are tabulated in Table 7 for a wide variety of materials of interest including 2024-T3 aluminum. Results of the analysis are presented graphically in Figure 4 where ballistic limit velocity is plotted against projectile diameter for three impact angles. Note that the impact angles presented in Figure 4 are the complements of the angles appearing in equations 1 to 5. The angles in the figure are measured between the target surface at the impact point and the trajectory of the incoming projectile.

The plots in Figure 4 indicate strongly that the theory predicts airframes will rarely, if ever, be perforated by tire-lofted stones. This is because a minimum of 75 m/sec (148 knots) would be required to produce perforation when stoney pellets with equivalent dimensions of 25 mm (21.7 grams) are launched against the surface at an impact angle of 60 degrees.

As stated earlier in this section, the reliability of empirically derived relationships outside of the range of the treated data is suspect. An attempt was made to obtain an indication of the reliability of the current theory by comparing results with those obtained during unrelated investigations at the University of Dayton several years ago. It was found, for example, that 25 mm (21.7 grams) diameter granite projectile launched at a 2024-T3 aluminum target 4.8 mm thick at an impact angle of 21 degrees achieved perforation at a velocity of 610 m/sec. Equation 5 was evaluated for this impact situation and produced a prediction of 212 m/sec for the ballistic limit velocity--just over 1/3 the measured value. As stated before, agreement between prediction and experiment is poor. For another comparison, data in Reference 15 give limit velocities of 500 m/second for a 2.65 grain (.17 grams) fired at a 30 degree angle from the vertical against 1.5 mm 2024-T4 aluminum plate. Since T4 plate is harder than T-3, these data also indicate that the estimate made by equation 5 is low.

Clearly then, this area requires experimental investigation to evaluate in detail the hazard of lofted debris perforating aircraft skin. The checks indicate, however, that theory does appear to underpredict impact velocities required for perforation. Therefore, the curves presented in Figure 4 are probably pessimistic and the probability of perforation of the skin of an airframe by a tire-lofted projectile might be

TABLE 7. EMPIRICALLY DERIVED CONSTANTS FOR EQUATIONS 1 THROUGH 5.

MATERIAL	C_{bf} M/S	b_f	h	f
ALUMINUM ALLOY 2024 T3	413	0.941	1.098	-0.038
TITANIUM ALLOY	491	1.314	1.643	0.011
FACE HARDENED STEEL	692	1.397	1.747	-0.206
MILD HOMOGENEOUS STEEL	806	0.963	1.286	-0.057
HARD HOMOGENEOUS STEEL	964	0.963	1.286	-0.057
CAST IRON	248	2.204	2.156	-0.018
PLEXIGLASS CAST	76.5	1.364	1.415	0.013
BULLET-RESISTANT GLASS	117	1.351	1.289	-0.035

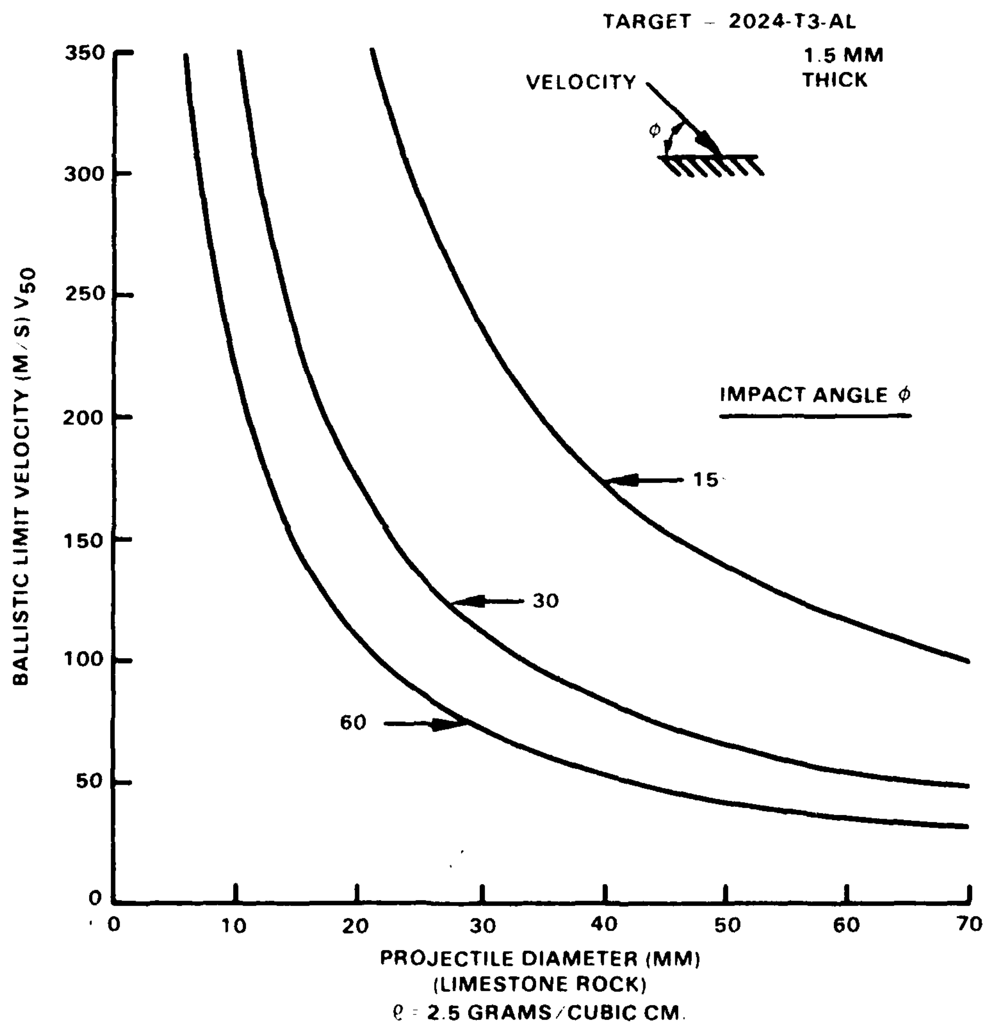


Figure 4. Ballistic Limit Velocity Versus Projectile Diameter for Various Impact Angles.

more remote than predicted. This is somewhat corroborated by the Boeing experience which did not indicate puncture of aircraft skins.

a. Airframe Damage

Spray from the tires will impinge on the airframe and cause surface abrasion. Because the spray velocity is not sufficient to cause the debris to penetrate the surface, however, it is unlikely that sufficient damage would be sustained as to cause a mission abort. Exposed antennas could be damaged to the extent that communications or navigation systems would be degraded.

b. Landing Gear Damage

Spray from the tires will impinge on various items attached to the landing gear or located in the wheel wells, such as hydraulic lines, electrical cables and taxi lights. The hydraulic lines and electrical cables will be subjected to abrasion, but it is unlikely that they will be severed. Taxi lights, however, are very likely to be broken. The landing gear, itself, would probably not be damaged.

c. External Stores Damage

Spray from the tires will impinge on external stores and cause surface abrasion. There is a low probability that the debris will penetrate external fuel tanks. The debris, however, could cause sufficient damage to radar or infrared domes on external stores to degrade system operation. The size of the particles which cause damage and the amount of degradation resulting cannot be determined at this time.

d. Mission Aircraft

(1) F-4

As shown in Figure 5, a limited amount of debris from the nosewheel tire may be sprayed into the engine inlets; but most of the debris will be sprayed on the lower surfaces of the fuselage, wings, and stabilators. Some damage to the radomes of fuselage-mounted SPARROW missiles should be expected. USAF data indicated a moderate rate of F-4 FOD incidents with a very small percentage specifically attributed to asphalt, rocks, and concrete.

(2) F-15

As shown in Figure 6, a very limited amount of debris from the nosewheel tire may be sprayed into the engine inlets, with most of the debris being sprayed on the lower surfaces of the fuselage, wings, and tail. Some damage to the radomes of fuselage-mounted SPARROW missiles should be expected. USAF data indicated a moderate rate of F-15 FOD incidents with a

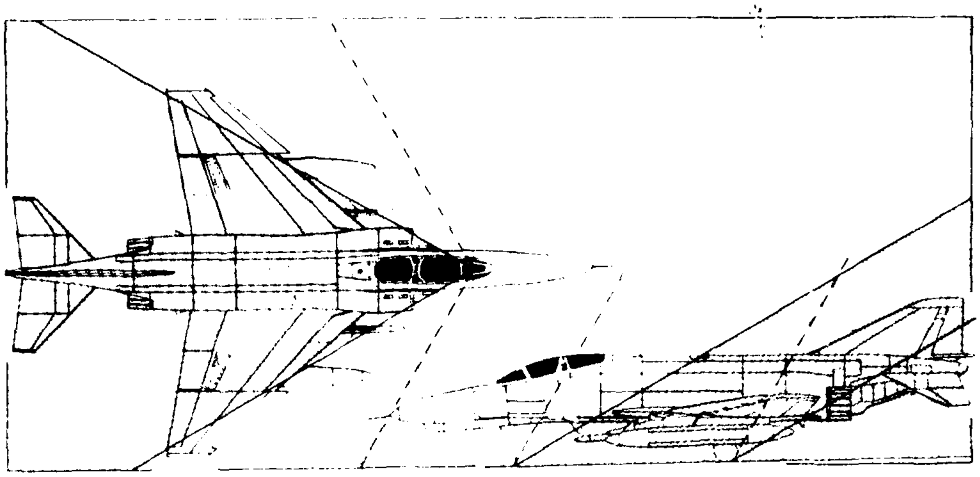


Figure 5. F-4 Tire Spray Pattern.

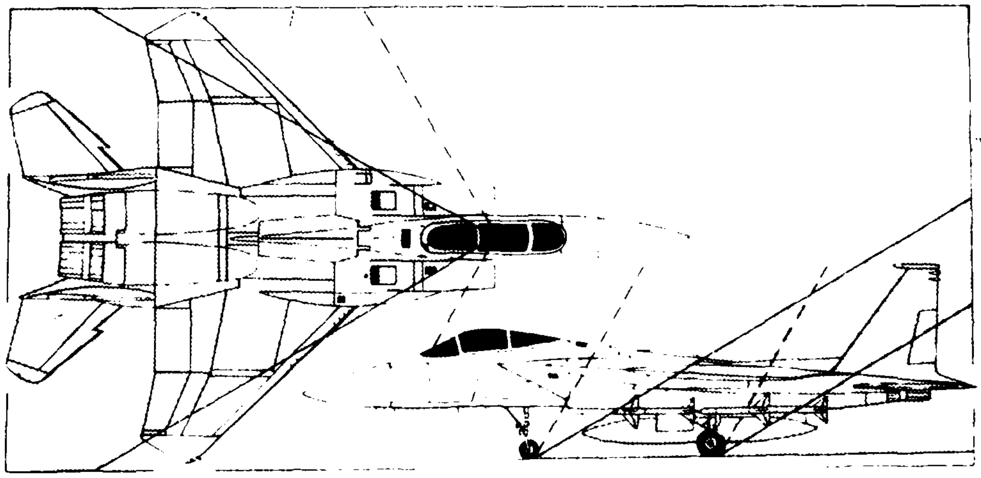


Figure 6. F-15 Tire Spray Pattern.

very small percentage specifically attributed to asphalt, rocks and concrete.

(3) F-16

As shown in Figure 7, debris from the nosewheel should not be sprayed into the engine inlet but should impact on the lower surfaces of the fuselage, wings, and tail. The low location of the engine inlet, however, appears to be conducive to the formation of an inlet vortex. Some ingestion of surface moisture that contributed to inlet icing has been attributed to the existence of an inlet vortex.

(4) F-111

A limited amount of debris from the nosewheel tire may be sprayed into the engine inlets, but most of the debris will be sprayed on the lower surfaces of the fuselage, wings, and tail. USAF data indicated a moderate rate of F-111 FOD incidents with a small percentage specifically attributed to asphalt, rocks, and concrete.

(5) A-10

As shown in Figure 8, an extremely limited amount of debris from the nosewheel tire may be sprayed into the engine inlets with most of the debris being sprayed on the lower surfaces of the fuselage, wings, and tail. USAF data indicated a moderate rate of A-10 FOD incidents with none specifically attributed to asphalt, rocks, and concrete. The high location of the engine inlets appears to preclude the ingestion of debris as a result of inlet vortex formation.

(6) C-130

An extremely limited amount of debris from the nosewheel tire may be sprayed into the engine inlets with most of the nosewheel spray impacting on the lower surface of the fuselage. Spray from the main landing gear tires will impact in the wheel well as well as on the aft fuselage. USAF data indicated a low rate of C-130 FOD incidents with none specifically attributed to asphalt, rocks, and concrete. There is evidence that an unknown number of commercial operators of C-130 aircraft without deflectors have been operating from gravel runways without encountering significant FOD.

e. Summary

The information collected for this research (e.g., specs, critical incident reports, etc.) was searched to determine the limits on the particle sizes which, if ingested into an engine, would cause major damage (i.e., engine failure or cause indications which would lead to an engine shutdown). The estimation of the limits on particle size is complicated by the fact that different engine designs exhibit different tolerance

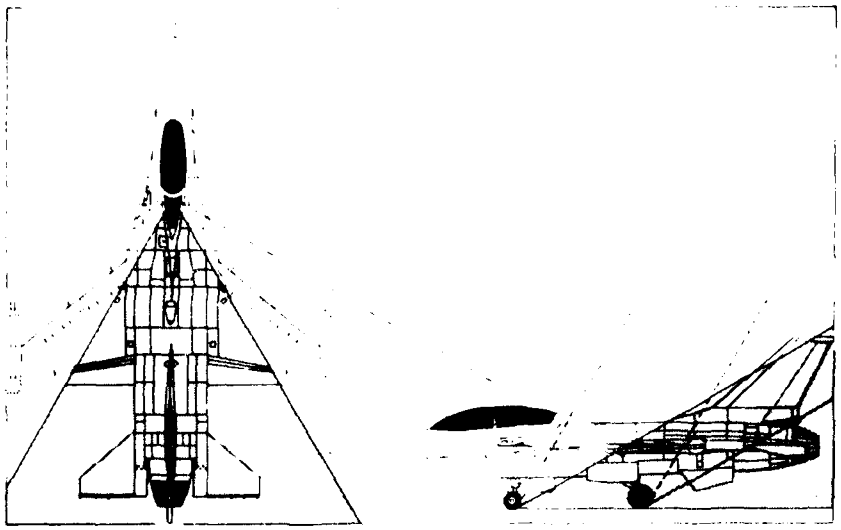


Figure 7. F-16 Tire Spray Pattern.

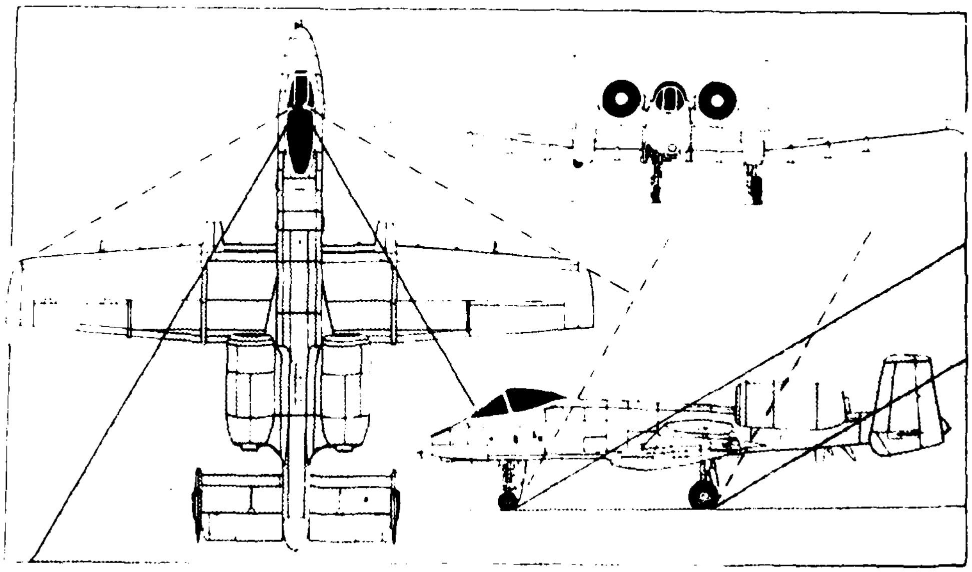


Figure 8. A-10 Tire Spray Pattern.

levels. For example, some engines were quoted as being rather tolerant (e.g., the J-79) and a difference was noted between turbofan and turbojet engines. There are, however, no numerical data as to the amount of difference. The difference in tolerance was mainly explained in terms of the fan-compressor geometries.

The limits that were established are shown in Figure 9. Only two levels could be established: sure safe and sure kill. It is indicated that dust and fine sand are not judged to cause failures if the exposure is that associated with takeoffs and landing. On the other extreme, a large hard object, such as a 1/4 inch diameter bolt, 2 inches long, made of steel will cause sufficient damage to cause engine shutdown. Also, it should be noted that a single measure of the lethality potential of the object has not been identified.

It should be noted that the FAA requires engines be tolerant to ingestion of some amount (dependent on inlet size) of 1/4 inch diameter gravel (hardness not specified). However, there is insufficient data on the engines used in the mission aircraft of interest to this study to judge their tolerance to this gravel ingestion.

5. DATA BANKS

The material from Reference 10 (FOD damage to Navy aircraft) was reviewed. The data set supplied was a listing from a computer-based data bank which gives a short (2 to 3 sentences) summary of the incident and cause of damage. One hundred and twenty six mishaps (causing immediate engine shutdown and removal) were listed in the material supplied. Another 71 incidents were listed as unsatisfactory reports (UR) wherein inspection after flight disclosed some damage to the engine. Eight incidents in each category - for a total of 16 out of 197 - were related to this study.

In the mishap category, engine damage on an A-4J was caused by an object as big as a pilot's nylon bag for an oxygen mask. In no other mishap was the object size specified. In the UR category, several instances of damage were noted due to particles of concrete or non-skid material detached from the flight deck. In no instance was the size of the particle given.

Another listing (Reference 9) from a data base was provided which listed only FOD as a cause. In this list, bird strikes were indicated as such. Of 116 entries, only 12 were listed as caused by FOD, (other than bird strikes) but in no case was the object which caused the FOD identified.

In all of the cases of FOD, the causes of which were related to the scope of this study, the damages were to engines. No entry noted damage to airframes. Given the understanding of aircraft operations relative to FOD (e.g., cleanliness of ramps), this finding is not surprising; however, there is little actual operational data from which to draw inferences.

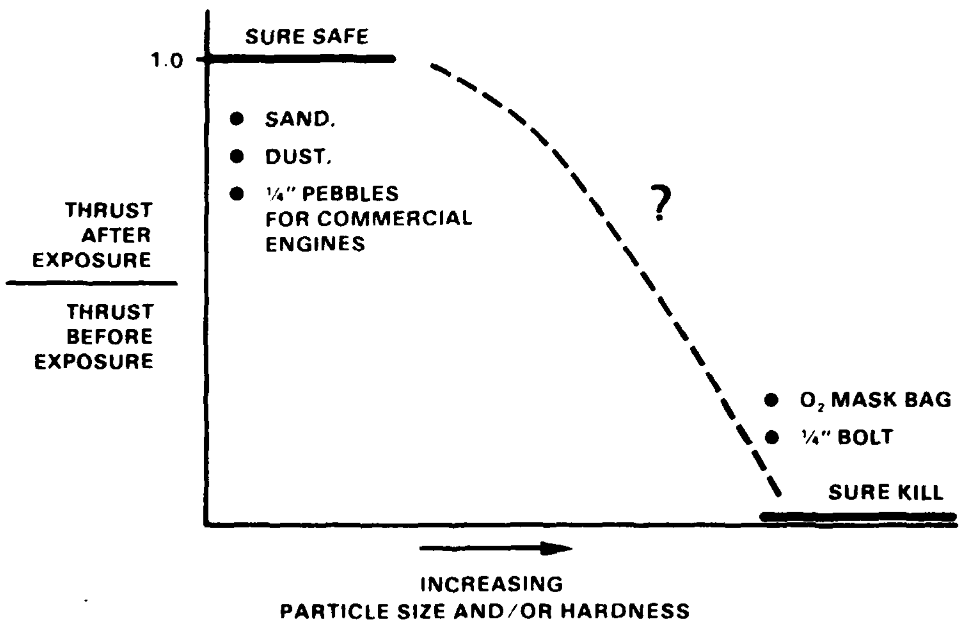


Figure 9. Susceptibility of Aircraft Engines to Damage by Foreign Objects.

The Air Force Inspection and Safety Center supplied data in a briefing chart format (Reference 13). An extract (Figure 10) shows that, in general, the incidents stemming from asphalt, rocks, and concrete are few (8 of 241 incidents). In these incidents, the proven source is given, but the size of the particle is not indicated. A large number of causes are listed as unknown. From the same source (Reference 13), the prevention practices are listed in Table 8. As can be seen by this list, the distinguishing feature is that, with one exception, each practice is an attempt to keep the aircraft from being exposed to a potential FOD hazard.

As can be understood from the previous discussion, due to the data reported, the FOD statistical data bases provide little insight into the details of the mechanisms involved, or the size of objects which caused the damage.

6. RUNWAY SURFACE AND ENVIRONMENTAL CONDITIONS

a. Policy

AFR 66-33 emphasizes the need to clean aircraft parking ramps, taxiways, and runways. The airlines, individually and collectively through the Air Transport Association of America (ATA), also exert pressure on airport operators to keep parking ramps, taxiways and runways free of debris. The ATA, for example, has established a Director of Airport Facilities as the coordinator of an industry-wide program to monitor conditions at the 100 largest US airports.

b. Experience

The military and FAA FOD data shown in Figures 11 and 12 indicate very few reportable FOD incidents are attributed to objects originating on the surface. Even fewer identify pebbles, rocks, gravel, etc., as the cause since most surface induced FOD incidents are reported as having been caused by unknown objects. From the data reported, it appears that policy is well implemented.

Not all foreign object encounters are reportable as FOD incidents. Cut tires, for example, do not appear in the FOD incident data, even though the tires may be damaged such that a takeoff would be hazardous. Engine blade nicks that can be blended without the removal of an engine component are also not normally reported.

Informal data on cut tires have been used by the military and airlines as indicators of runway surface conditions. One airline reported a significant increase in the number of cut tires and FOD at a European airport whose concrete runway surface had deteriorated and needed resurfacing. The Tactical Air Command has also observed a significantly greater frequency of cut tires at airfields where strong prevailing winds blow debris across airfield surfaces.

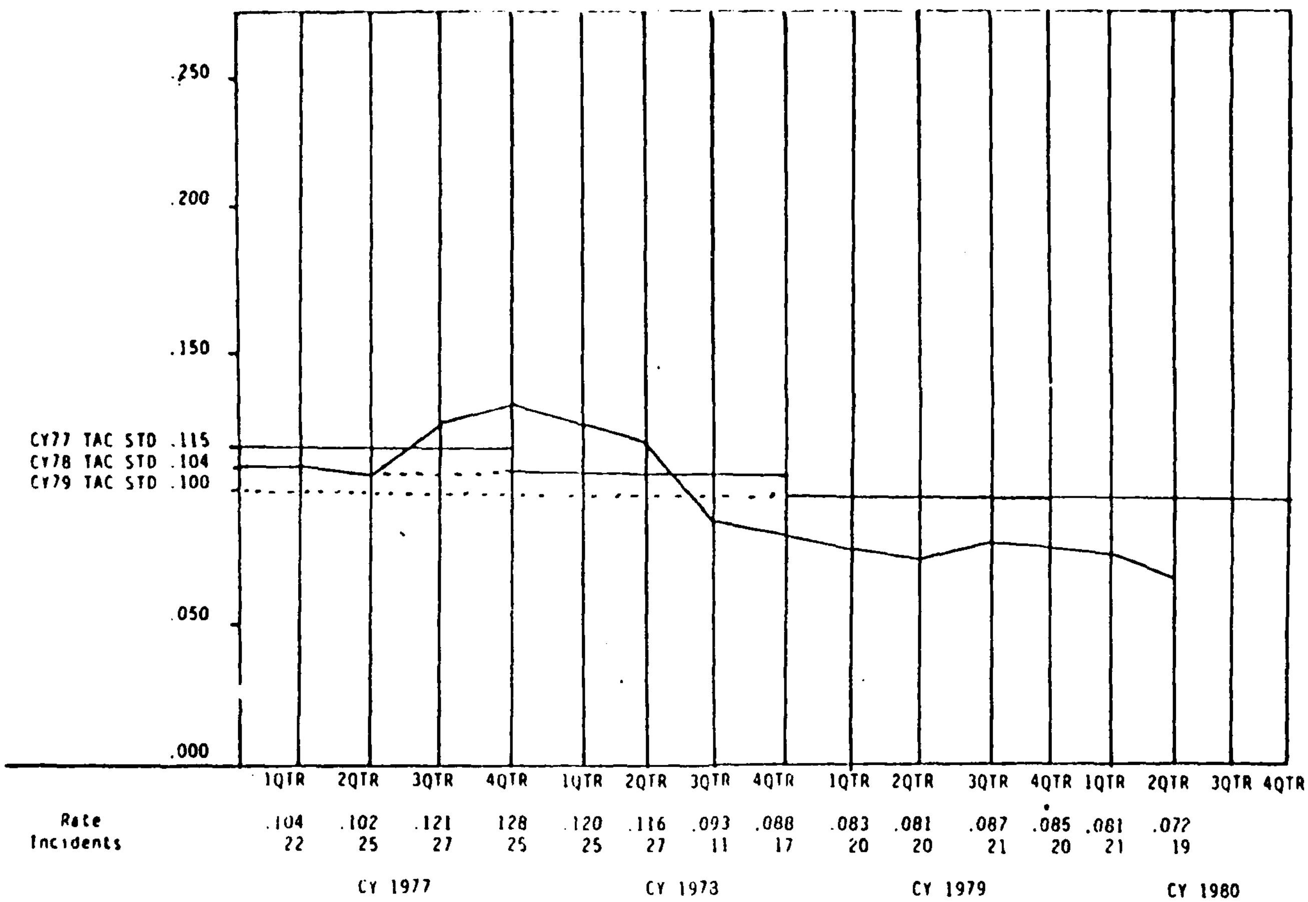
(INTENT FOR FLIGHT ONLY)

	UNDETERMINED	BOLT, SCREW, NUT, RIVET FASTENER	A/C HARDWARE (OTHER)	METAL OBJECT	TOOLS, FORMS, RAGS, HEADSETS, FLASHLIGHT	ASPHALT, ROCKS, CONCRETE	SAFE PINS, GROUND WIRES	AGE, COVERS	RICOCHET	TOTAL	(ICE (NOT IN TOTAL)
F-4	38	19	7	7	0	0	0	0	1	67	1
T-38	15	1	5	1	5	1	2	2	0	32	0
F/FB-111	11	8	3	5	1	3	0	1	0	32	0
F-15	11	8	1	0	1	1	0	0	1	23	0
F-5	4	1	0	3	1	0	1	0	0	10	0
C-130	10	0	0	0	0	0	0	0	0	10	0
TOTAL ALL AIRCRAFT	124	51	22	18	9	8	4	3	2	241	25
MISHAPS	124	73				44				241	
%	51.5%	30.3%				18.3%					

Figure 10. FOD Causes 1979 (Through September) (Air Force Inspection and Safety Center Briefing Charts).

TABLE 8. OPERATION AND MAINTENANCE PREVENTION PRACTICES (AIR FORCE INSPECTION AND SERVICE CENTER BRIEFING CHARTS).

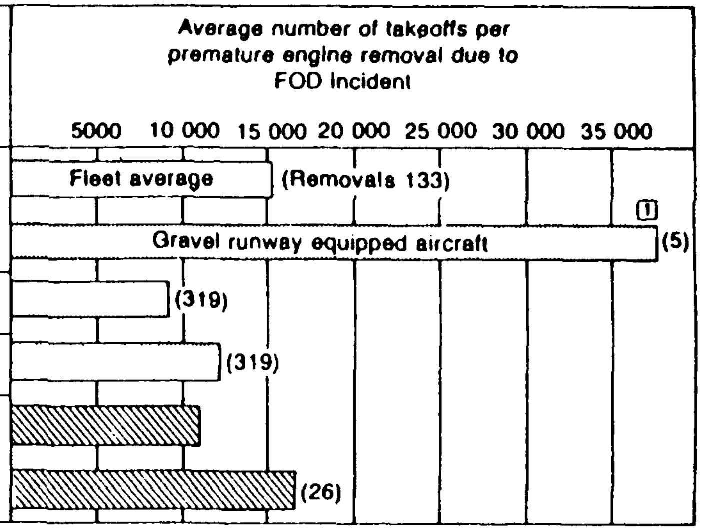
- ADEQUATE TAXI INTERVALS
- EFFECTIVE SWEEPER PROGRAM
- EFFECTIVE TOOL CONTROL PROGRAM (CTK)
- NONDESTRUCTIVE INSPECTIONS (X-RAY)
- CONTROLLED BENCH STOCK
- INTAKE REPAIR RIVET ACCOUNTABILITY
- USE OF BUNNY SUITS
- PROTECTIVE COVERS FOR INTAKES AND OPENINGS
- PROPER MAINTENANCE OF INTAKE SCREENS



Number per 1000 engine flying hours

Figure 11. FOD Incident Rate for TAC.

Airplane	Engine	Engine Hilite ground clearance h-(inches)	$\frac{h}{D_{HL}}$
737	JT8D	31	.725
DC-9	JT8D	98	2.23
Excluding center engine			
727	JT8D	140	3.30
Inboard engines only			
707	JT3D	43	.895
747	JT9D	54	.616



[1] 1978 - 9 reporting airlines (52569 takeoffs) 2 FOD incidents
1977 - 13 reporting airlines (79,401 takeoffs) 1 FOD incidents
1976 - 6 reporting airlines (59,330 takeoffs) 2 FOD incidents

$^{*}D_{HL}$ Engine Hilite Diameter

Figure 12. Engine FOD Data (P&W Fleet Data).

c. Applicability

Most operational experience and data have been accumulated on relatively clean surfaces not representative of surface conditions of interest to this study. There is abundant evidence, however, that the incidence of ground induced FOD increases significantly whenever the surface conditions deteriorate or when cleanliness standards are relaxed. Nevertheless, there is no data to indicate total exposure to hazard in any case, so the fraction of exposures which results in damage is not determined.

7. TECHNIQUES FOR PREDICTING FOD

a. Tire Spray Characteristics

The mechanism by which tires spray debris is well understood qualitatively, but there do not appear to be any quantitative data available on spray characteristics that relate debris size, velocity, and distribution pattern. Tests are required to obtain the needed data. Suitable testing facilities are available.

b. Engine Damage Prediction

Similarly, engine FOD resulting from the ingestion of debris is well understand qualitatively, but there do not appear to be any systematic tests using controlled pebble sizes that can be used to predict damage except for 1/4 inch gravel used in FAA tests.

c. Prediction Methodology

It may be concluded that the current level of technology permits only a qualitative understanding of FOD potential. No quantitative relationship has been established between debris characteristics and the extent of damage. Consequently, no quantitative prediction method is available. A testing program is needed to quantify the relationship and to permit the development of a prediction methodology.

8. ACCEPTABLE FOD LEVELS

Because no quantified relationship has been established between debris characteristics and the extent of damage, there are no meaningful quantita tive criteria for FOD levels. As discussed in Section II, the susceptibility of engine inlets to foreign object ingestion and the vulnerability of components to damage differ among aircraft. For example, it is apparent that the C-130 can tolerate the presence of substantially more debris than fighters can tolerate. No acceptable FOD levels can be established, however, until a testing program is accomplished and a prediction methodology is developed.

The Tactical Air Command has established a standard for the rate of FOD incidents (e.g., 0.100 incidents per 1,000 engine flying hours in calendar year-79) and has set a goal of zero incidents. This standard is an important command initiative, but it should be recognized as one which is designed for peacetime operations. As such, it was not determined how this might apply to FOD levels under the conditions of interest to this study; there was no indication of acceptable wartime incident rates.

9. FOD PREVENTION TECHNIQUES

a. Operational Procedures

A number of operational procedures can be used to reduce the probability of debris ingestion:

(1) Engine Starting

Because of the presence of baggage debris (tags, buckles, straps, locks, etc.) on the parking ramps at commercial airport loading gates, some commercial airlines have delayed starting engines until the aircraft has been pushed back to an area free of debris. Other airlines restrict the amount of engine power that can be used in the loading gate area.

(2) Taxi

Minimum engine power levels should be used during taxi to reduce the probability of debris ingestion. Boeing recommends that nosewheel steering be used during taxiing on gravel surfaces. Boeing further recommends that all turns on gravel sufaces be as large a radius as possible to avoid digging in the nosewheels. If the airfield surface between the parking area and the runway is particularly rough or debris-laden as a result of bomb damage, consideration should be given to towing aircraft to the runway rather than risk debris ingestion by taxiing.

(3) Takeoff

Boeing recommends that a rolling takeoff be performed on gravel runways. This is accomplished to avoid prolonged engine operation at high power while stationary, the alternative takeoff procedure. The Marines, who operate AV-8 HARRIER V/STOL aircraft from unconventional surfaces, frequently use a rolling takeoff in the VTOL mode to avoid engine reingestion problems.

(4) Landing

The landing should be planned to avoid landing gear touchdown in known debris-laden areas if at all possible since tire spray is at a maximum during tire spin-up (as quoted in the Boeing experience on gravel runways: The Boeing Commercial Airplane Division Substantiation for 727

Gravel Runway Operations D6-18498). Boeing recommends that the reverse thrust of the 727 side engines be limited to idle power and that the thrust reversers of the 737 engines be stowed before the aircraft slows to approximately 70 knots.

b. Landing Gear Deflectors

(1) Commercial Aircraft

For 737 aircraft operation on gravel runways, Boeing has incorporated a nose gear deflector, shown in Figures 13 and 14, and the main gear deflector, shown in Figure 15, to suppress tire spray. Boeing has also developed between-the-wheels gravel deflectors for the nose and main landing gears of 727 aircraft. Some DC-9 aircraft have landing gear deflectors installed to prevent the engine ingestion of water sprayed by the tires, but these deflectors also serve to reduce the spray of debris.

(2) Military Aircraft

The Naval Air Systems Command is sufficiently concerned about the potential F-14 engine FOD threat posed by nose tire spray that it has authorized the testing of a nose gear deflector. The deflector, shown in Figure 16, was designed by the Naval Air Test Center, Patuxent River, MD, and is being tested at the Landing Loads Track Facility at the NASA Langley Research Center, Hampton, VA. Tests of the F-14 nose landing gear will be conducted over known levels of debris at simulated taxi speeds. The spray pattern from the nosewheel tires will be determined with and without the deflector installed. Similar deflectors have been observed on some USSR tactical fighter aircraft.

Due to the pertinence of this test to the subject of this report, some additional discussion was felt appropriate. During a tour of duty involving operation of F-14 aircraft, CDR John K. Ready, USN, suspected that F-14 engine FOD was being caused by debris from runways and taxiways being sprayed by the nosewheel into the engine inlets. During a subsequent tour of duty in the Strike Aircraft Diretorate at the Naval Air Test Center, Patuxent River, MD, he decided to test the theory. Two flight test engineers at the Strike Test Directorate, Mr. Gary Rasponi and Mr. Scott Chasen, designed and fabricated the experimental nosewheel deflector shown in Figure 16.

The experimental nosewheel deflector was designed to withstand wind loadings in flight, but no flight tests have been conducted. It has been installed, however, on an F-14 aircraft and ground checked to ensure that adequate wheel well clearance exists when the nosewheel is retracted. The deflector was then removed from the aircraft and sent to the NASA Langley Research Center for tests.

Tests of the experimental nosewheel deflector were authorized by the Naval Air Systems Command by an Air Task and were to be

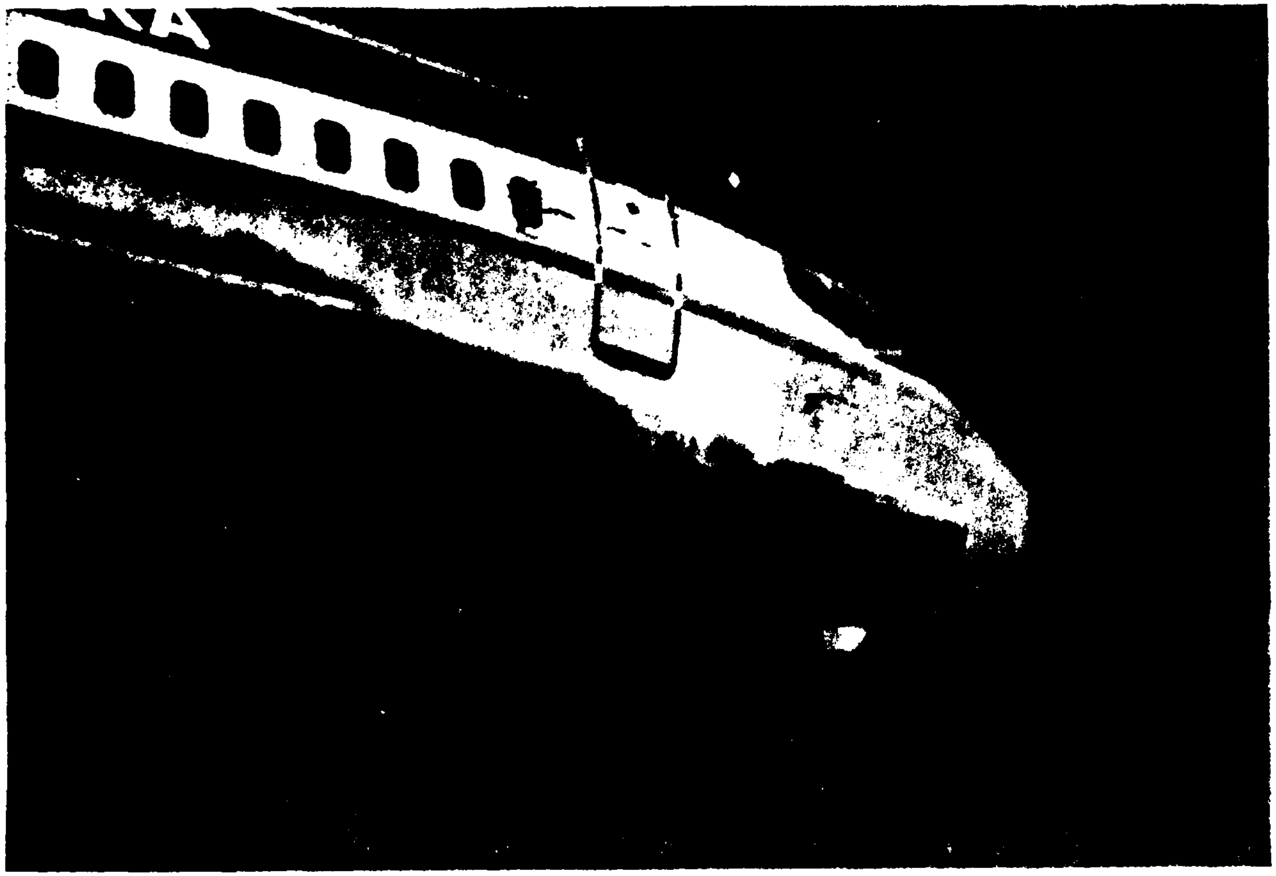


Figure 13. Boeing 737 Nose Landing Gear Deflector.

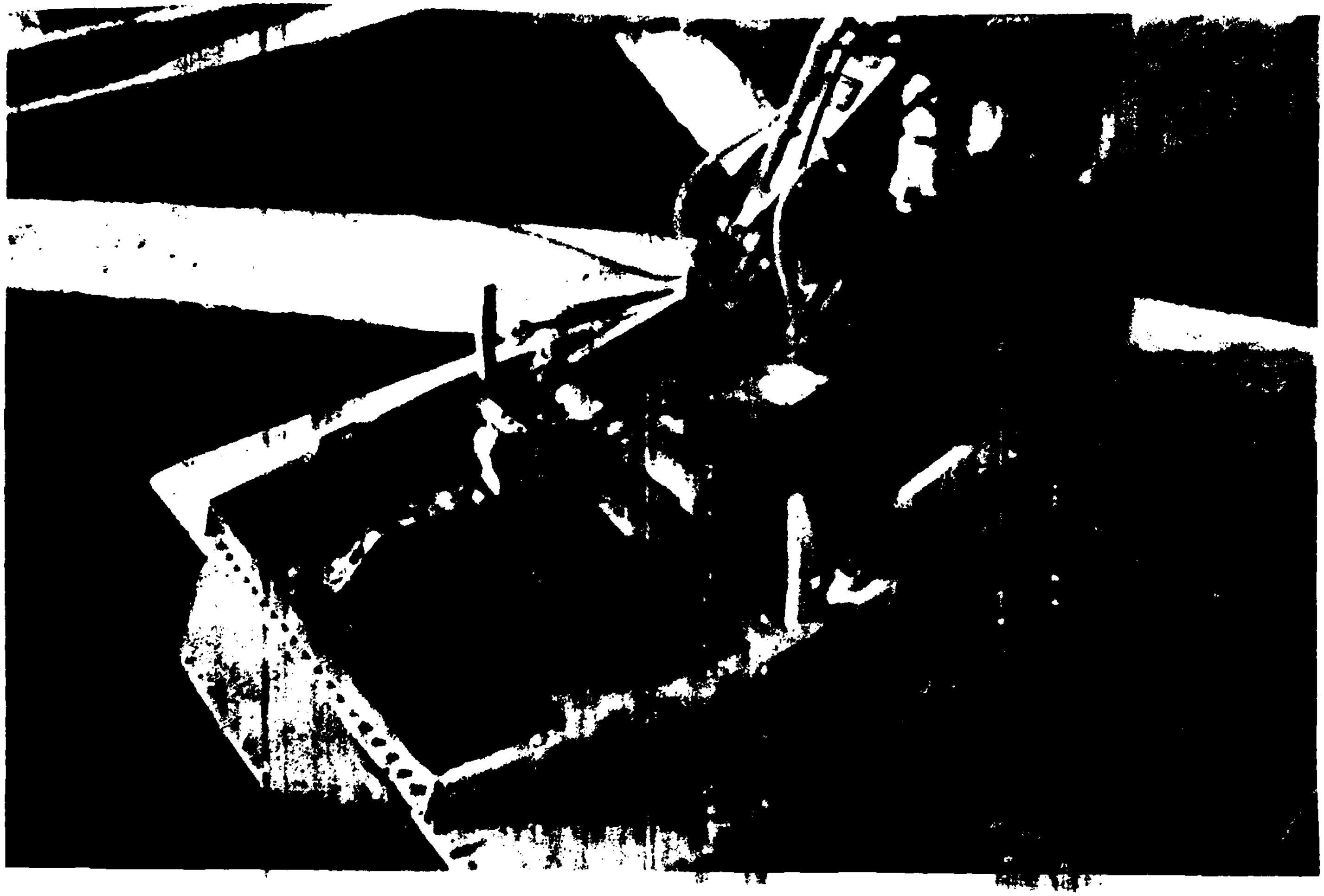


Figure 14. Boeing 737 Nose Landing Gear Deflector - Close-Up View.

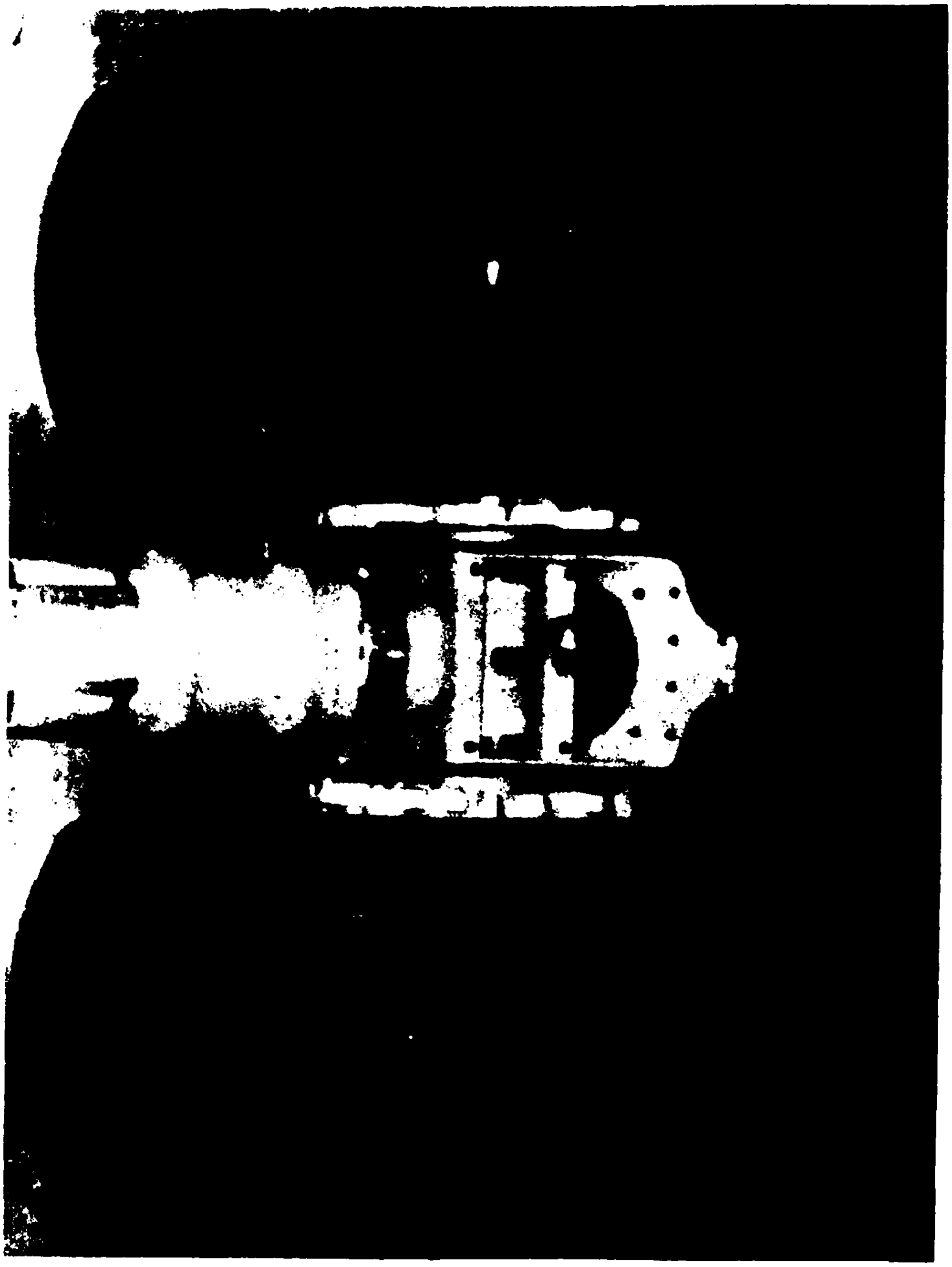


Figure 15. Boeing 737 Main Landing Gear Deflector.

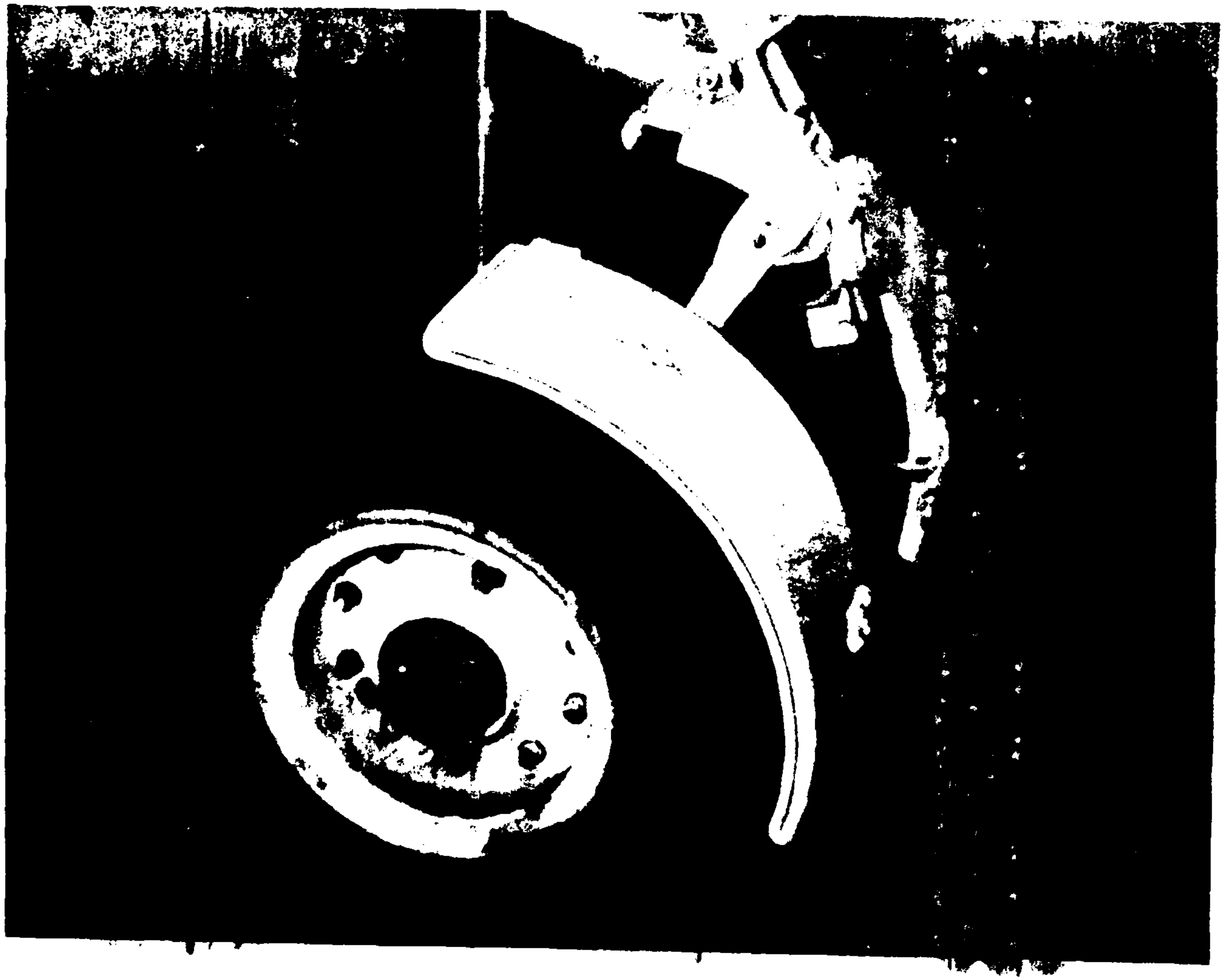


Figure 16. Experimental F-14 Nosewheel Deflector.

conducted during 1978. However, because of higher priority workload on the Landing Loads Track (related to the Space Shuttle), the tests were delayed. An F-14 nose landing gear has been mounted on a carriage together with the arrays of bins, sized for the dimensions of the engine inlet flow patterns, to capture the debris (Figure 17). High speed camera coverage of the spray pattern will be obtained by cameras mounted ahead, above, and to each side of the landing gear.

The nosewheel spray pattern is being tested with and without the deflector installed. Debris consisting of nuts, washers, bolts, safety wire, rocks, crushed concrete and pebbles will be distributed on the track. The distribution of the particles used was determined in part by taking material that had been picked up by a ramp sweeper. Also, a quantity of crushed stone used by AFESC for bomb-damaged repair of craters was provided and was applied on the track in 15 foot sections and at different densities. On 26 May 1981, BDM witnessed two test runs conducted at 90 and 120 knots speeds. A summary of the test data to date was obtained. Discussions with the test personnel elicited some insights on the results obtained from the 31 test runs completed. This data and brief description of the observations acquired allowed the preliminary conclusions documented in Appendix I.

c. Inlet Vortex Suppression

(1) Research

In Reference 2, a Douglas Aircraft Company engineer reported that a downward directed jet prevented the formation of the inlet vortex. He concluded that the blowaway jet represents a simple, safe, and economical scheme for greatly reducing the amount of engine damage expected due to material pickup from the runways. In Reference 3, two Boeing Company engineers reported that for blowaway jets to be most effective they should be directed rearward, be as close to the surface as practical, and be located ahead of the ground plane stagnation point.

(2) Commercial Aircraft

Boeing has incorporated the vortex dissipators, shown in Figure 18, on 737 aircraft for operation on gravel runways. This modification, in combination with the landing gear deflector installation discussed previously, has permitted operations from gravel runways with FOD rates comparable to those experienced by unmodified 737 aircraft operating from conventional runways. Blowaway jets with a different configuration were incorporated in DC-8 aircraft, but their use has been discontinued because of inconclusive evidence of their effectiveness in reducing FOD.

(3) Military Aircraft

A blowaway jet was incorporated in the engine inlets of the A-6 aircraft as a result of a specified requirement that it be capable of

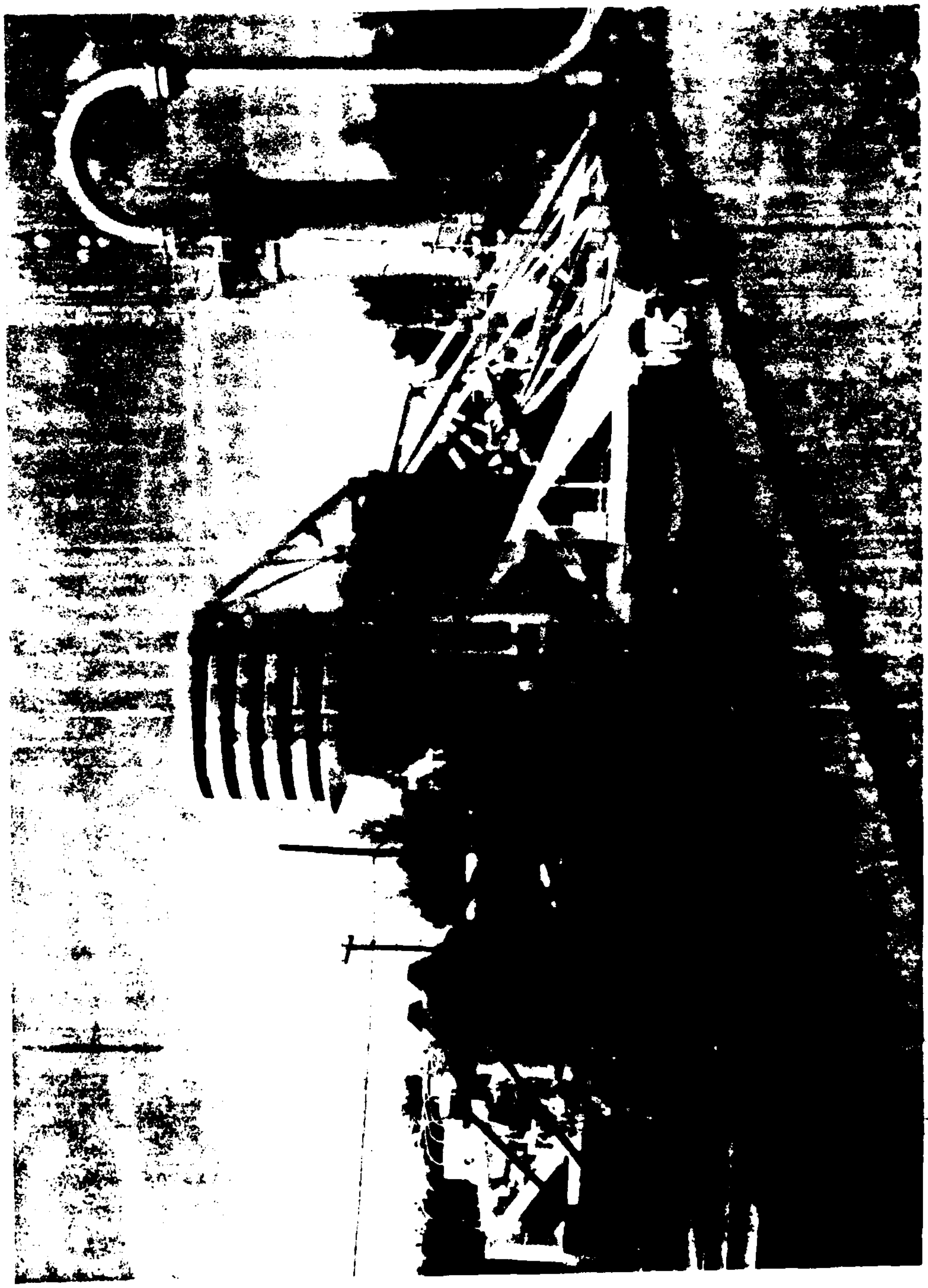


Figure 17. NASA Langley Test Facility.

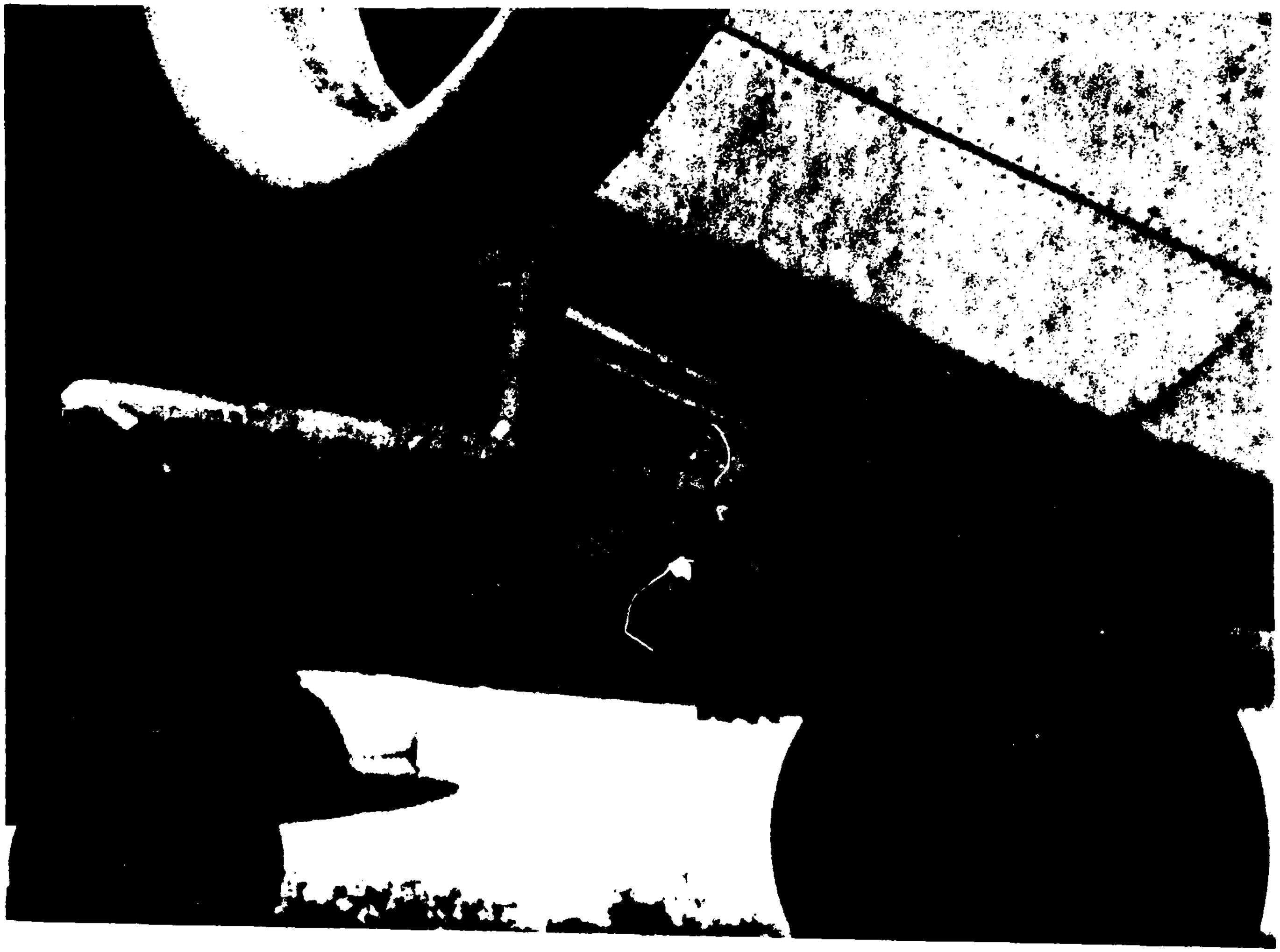


Figure 18. Boeing 737 Engine Inlet Vortex Dissipator.

operating from temporary airfields. Grumman tests showed that the blowaway jet was effective in dissipating the inlet vortex. Similar vortex suppression systems were incorporated in F-14, F-18 and F-111 aircraft, but their use has been discontinued. The discontinuance of vortex suppression systems in all but the A-6 aircraft is attributed to the absence of quantitative data regarding their effectiveness in reducing FOD.

d. Shielding

Boeing incorporated metal shields covering parts of the 737 main landing gear hydraulic brake lines and the speed brake control to protect them from tire spray during operation on gravel runways. Lockheed-Georgia developed protective devices for items in the wheel wells of C-130 aircraft in anticipation of operation on gravel runways. Lockheed-Georgia did not incorporate the protective devices, however, but believes that commercial C-130 operators have incorporated their own shields as needed.

e. Surface Sweeping

AFR 66-33 directs the use of mechanical vacuum sweepers for commercial aircraft parking ramps, taxiways, runways, and other areas if needed. It also directs that magnetic sweepers be used, if available. Special care must be given to cracks and crevices where debris may collect. One major airline has recently procured 75 magnetic sweepers to be used in conjunction with mechanical vacuum sweepers to keep parking ramps free of debris.

SECTION IV

ASSESSMENT OF THE NEEDS FOR TECHNOLOGY DEVELOPMENT

1. INTRODUCTION

This section defines the needs and shortcomings of the predictive technology base associated with foreign object damage (FOD) phenomena. This assessment is based upon the information gathered from all sources and thus represents a synthesis from all available data. The total scope of all of the sources which can influence FOD is complex due to many interactions. For example, FOD may be caused by debris lying on the surface or created by tire or jet blast interaction with a surface. Because of these and other complexities and interactions, it was felt that a systematic, detailed explanation of the processes involved and the state-of-the-art knowledge would help provide an understanding of what might be accomplished in any further research.

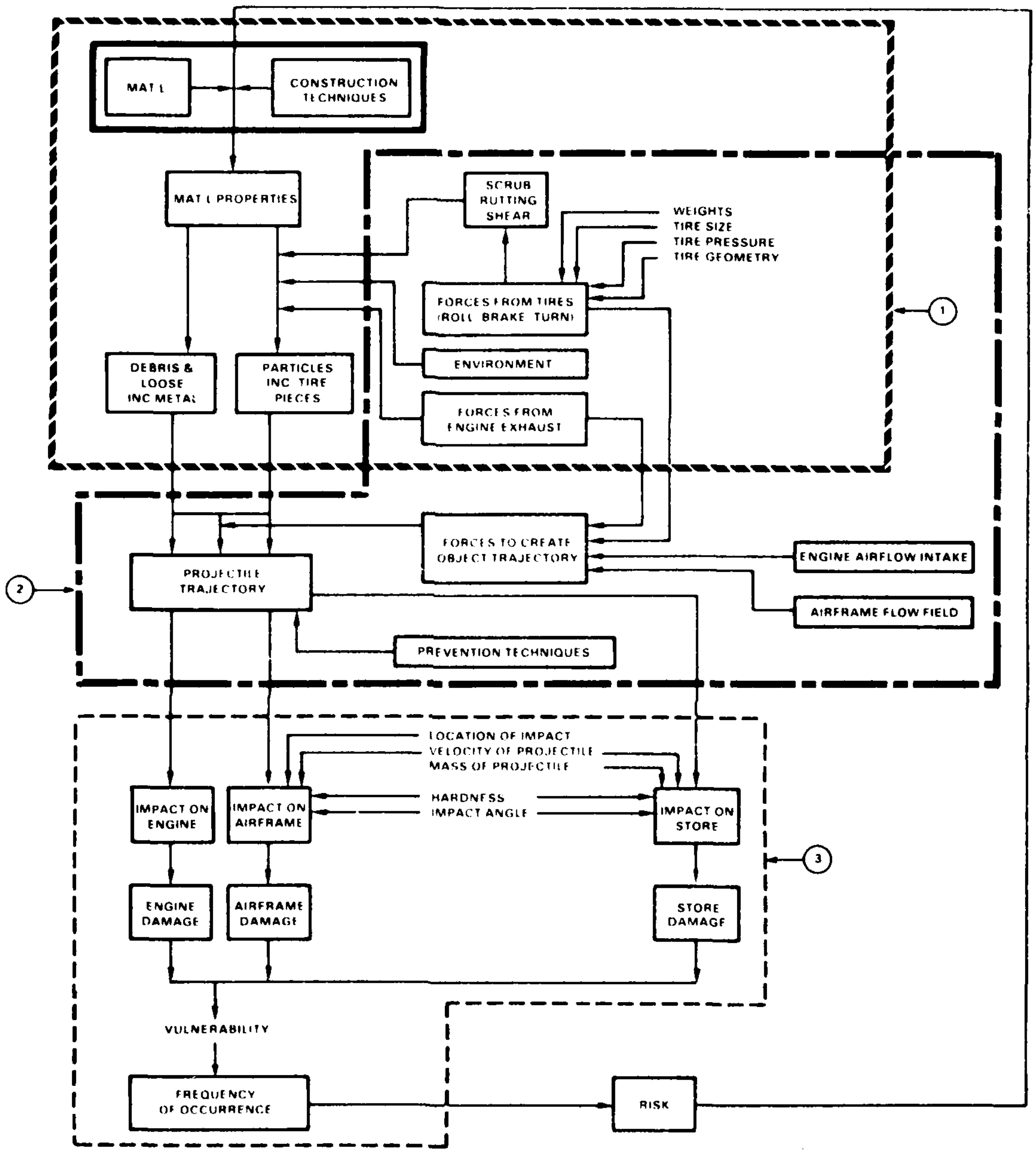
2. OVERALL INTERACTIONS

To portray the overall scope and the factors which influence the FOD process, a flow diagram is shown in Figure 19. The diagram portrays the sources of particles, the processes by which they ultimately become projectiles, and the mechanisms which cause damage to aircraft or stores. Also shown is the interaction among the various factors, and the position in a sequence of events where they may occur.

For the purposes of this discussion, particles are loose material (created by a variety of sources) which may exist on the surface. Upon achieving a trajectory which causes them to become potential causes of FOD, they are termed projectiles.

The objects which ultimately cause damage start as particles. These particles may be loose material on the surface such as debris, bolts and nuts, pieces of rock used in construction, etc., or they may be formed by tire-surface interaction or jet blast-surface interaction. Some particles so formed may not cause damage, because they may be too small, soft, or not subject to sufficient forces to produce a projectile. In Figure 19, the processes creating projectiles are shown surrounded by the dashed line and indicated by 1.

Once a particle has been subjected to some force such as an aircraft flow field, tires, jet blast, or engine air intake airflow, it can be propelled on a trajectory which can cause it to either impact the airframe or external stores, or enter an engine intake (indicated in Figure 19 by the area inside of the boundary labeled 2).



1. HOW IS AN OBJECT FORMED?

2. HOW DOES THE OBJECT BECOME A PROJECTILE?

3. WHAT PROJECTILE IMPACTS CAN AIRCRAFT SURVIVE?

Figure 19. Origin of FOD and Impacts.

An understanding of the forces which can interact with a particle and cause it to have a trajectory which makes it a potential FOD projectile lead to attempts to modify the forces or the trajectories. Hence, one sees deflectors and fenders on aircraft nose gear and jets to dissipate the vortex produced by engine flow.

3. EVALUATION

Several items in the flow diagram represent forces and interactions which are conducive to an analytical, numerical, and engineering approach. These are:

a. Tire-surface interaction and the size particles developed therefrom,

b. Forces to create a projectile trajectory and the resulting trajectories,

c. Impact of object on engine parts, and

d. Impact of projectile on airframe.

None of these areas produced systematic, detailed, analytic understanding of all of the processes involved. Little or no engineering practice has been applied to any of these in a manner which can assist in an analysis of the problems. These are constituted by the area inside the boundary labeled 3.

A limited amount of tire-surface interaction has been tested (by the Air Force in the 1960s and early 1970s) and some analytics drawn (specifically, the work by Kraft). Most of this, however, has evaluated a flexible surface which is subject to rutting, like soft soil, in order to determine the surface deflections. The tests run did not focus on the microstructure of particle production which would produce a source of FOD. The mechanisms by which tire surface interactions produce particles which can become projectiles are not quantitatively described.

In reference to projectile impact on the airframe, there is ample penetration data, but mostly for very hard objects, such as bomb fragments and projectile slugs. The penetration ability of softer objects such as rock, macadam, or concrete has not been systematically tested. The engine tests are limited as discussed previously in the report.

The forces that might act on a particle (the second item above) to cause it to have a trajectory that would make it a FOD projectile are not subject at this time to a complete analytic treatment. Some qualitative statements have been established, but no numerical solutions exist. For example, the available information based primarily on tests in the mid-1950s indicates that FOD ingestion in the presence of an inlet vortex is a complex interaction of a disturbance of the particle by the vortex. This

vortex action supplies an initial trajectory, which then allows the particle to be captured by the general intake airflow and thus become a projectile which enters the engine. Despite tests at that time, no complete theoretical treatment exists.

Since the state-of-the-art information related to all of the steps in the FOD process are supported by so little numerical or engineering data, it is not possible to predict a FOD risk in the sense of a numerical probability. The state-of-the-art rests largely on the qualitative statements that have been made in the report. As the report clearly indicates, when there is judged to be a problem (e.g., B-737, F-14), a largely experimental approach is made to reduce FOD to some acceptable level. In short, there is no analogy in predicting aircraft damage due to FOD relative to an engineering discipline such as bridge design. Hence, if an engineering analysis is desired, one must start with fundamental tests in several areas and develop techniques from that base.

4. AIRCRAFT DESIGN

So far as is known, aircraft designed for the US military have not specifically included design criteria related to operations in an environment in which the FOD studied in this report may be present. The sole exception is the C-5A which, although designed to operate on soft (CBR-9), unprepared surfaces, is not known to have any design requirements related to an environment which may include the FOD considered in this report.

Engines are subject to the specifications noted earlier, which can relate to some types of FOD, but the link between the projectiles used in the specification and any type of runway surface was not established.

Several foreign aircraft (notably JAGUAR, FLOGGER [MIG-27], and MIG-17) are reported to have the capability to operate efficiently from grass strips (References 11 and 12). The design approach and calculations made are not known to the authors of this document.

The approach to aircraft design is apparently subject to an assumption that the type of FOD environment envisioned and evaluated by this report does not exist. Moreover, if any problems do occur, the inherent reaction is to change the environment to one in which no damage can occur (e.g., sweeping of ramps, inspection of inlets). Likewise, aircraft operations are adjusted to reduce exposure to potential FOD. This is normally followed by the procedures exemplified in the Boeing approach to the B-737, which essentially involves modifications after the fact to reduce damage levels to as low a value as possible, based largely on experiments and experience.

5. SUMMARY

Due to the complexities, interactions, and state-of-the-art, virtually all of these areas related to FOD require an indepth test and analysis

treatment to achieve a full, systematic, and analytic means of predicting FOD damage probabilities over a wide range of situations. Due to the status of the predictive technology, any comprehensive, analytic investigation will be long, expensive, and will necessarily involve several agencies of the USAF. Such a course is not suggested at this time, due to the broad based, interrelated effort required. Rather, given the state-of-the-art, program needs, and the ongoing activities, a selected test program is recommended for the near term.

The selected test program should be used to collect a limited amount of pertinent data (e.g., the F-14 nose gear tests). These test data would be fitted into the qualitative structure created in this report to initiate a quantitatively based understanding of the interactions and impacts. The information from the tests and the qualitative structure can then be used to identify more tests and the collection of selected data as opportunities arise (e.g., measure the formation of particles which result from load tests in the soft soil experiments). This will then systematically create a base of understanding from which theory and analytical procedures can be built for the future. In short, the basis of qualitative understanding systematized in this report should be carefully melded with experimental data in a planned manner. This will then permit recommendation for larger analytic and experimental efforts to be accomplished with a solid rationale which focuses on critical issues.

SECTION V

CONCLUSIONS AND RECOMMENDATIONS

1. CONCLUSIONS

a. General

The study of foreign object damage has been limited by lack of quantitative data and the judgmental character of many inputs. Subject to these restrictions, however, the following conclusions are made within the context of this analysis and pertain to the type of ground-induced FOD on which this study focused. Due to the lack of precise data, the individual findings cannot be prioritized. However, the few major findings are so noted.

The single major conclusion related to the principal objectives of this study follows. The most striking result from the investigation is the paucity of relevant quantitative data currently available. The general subject area has produced few systematic investigations and virtually no dedicated experiments. Insufficient data exist for reliable and quantitative assessment of any major problem addressed by this report. A complete analytic treatment for the problem or its parts is not available in the current state-of-the-art (SOA). Instead, a very limited empirical data base exists. For example, with respect to the flow field which produces inlet vortices and their ability to loft particles into engine intakes, the references (The Boeing Company Airplane Engine Foreign Object Damage, D6-44767, Vol. 1, Feb. 23, 1978) state that "no complete analysis of this region is available at this time." The current level of technology permits only a qualitative understanding of FOD potential. No quantitative relationship has been established between debris characteristics and the extent of damage. Consequently, no quantitative engineering-level design prediction method is available.

b. Types of FOD

(1) It is not possible to define quantitatively the acceptable level of debris for operations from unconventional and bomb-damaged airfield surfaces, over a wide variety of conditions. Aircraft modifications to prevent FOD are available which might permit operations from such surfaces, but their effectiveness must be demonstrated to justify their incorporation.

(2) Sand and dust, if limited to exposures during takeoff and landing, will not produce mission abort damage to engines. Sand abrasion on missile IR seeker heads and EO missiles such as MAVERICK should not be a problem for limited exposure of takeoff and landing.

(3) Aircraft engines are almost certainly subject to immediate and serious damage if they are allowed to ingest certain types of debris

which can be lofted from runway surfaces. Operations at particular airfields may expose the aircraft to only self-lofted debris, or to both self-lofted debris and debris lofted by other aircraft.

(4) Damage to jet engine fan and compressor blades constitutes the primary threat.

(5) A source of FOD can be tire pieces that result from landing and can be caused by repairs or AM-2 mats. While pieces of tire tread probably will not damage the airframe of the aircraft from which the piece originated, damage to the engine may occur if the piece is ingested.

c. Mechanisms of FOD

Design conclusions cannot be justified by the findings of our investigations due to lack of necessary data. The following general considerations for operations on unconventional and bomb-damaged runways can be made, however.

(1) Tires

(a) Debris lofted by landing gear tires constitutes the most severe threat to aircraft.

(b) Objects with potential to cause engine damage may be lofted from alternate runways by action of aircraft tires and aerodynamic flows (including engine exhaust or propeller slipstream). For aircraft with dual nose gear, interaction between the wheels can increase the number of objects which are thrown against the airframe and wheel wells.

(c) Pebbles and other small objects may be lofted by tire interaction with unconventional runway surfaces. Tread envelopment, tread pinching, and tread gripping project material at a variety of velocities and directions.

(d) Most tire-lofted debris occurs at angles within 30 degrees of the runway surface and tire plane. Occasionally, debris is lofted to 60 degrees.

(e) Debris lofting is affected by tangential loads from the tire footprint. These loads are increased over normal values by aircraft maneuvers (turning and braking).

(f) Spray concentrations were noted by Boeing to be particularly heavy during the tire spin-up at landing touchdown. This is indication that higher FOD-producing loads are present during this condition.

(g) Preliminary calculations indicate that debris from spray due to tires will probably not damage aircraft skins sufficiently to cause mission abort.

(h) Debris could cause sufficient damage to radar or infrared domes or external stores to degrade system operation.

(i) Stones or tire tread material lofted into wheel wells may cause mission abort and serious damage to vulnerable components (e.g., hydraulic lines).

(2) Engines

(a) Engines are subject to damage by ingested particals which may originate from tire lofting or ingestion by engine air in-flow (or some combination of the two). The relative amount of landing-gear-lofted debris and debris ingested solely as a result of engine air flow is not known, and different sources place emphasis on each.

(b) FOD data collected from engine incident reports have very limited information about the cause of FOD and no explanation for the small number of incidents which have been attributed to surface-induced FOD.

(c) Fanjets and turbojets undergo different damage mechanisms. Turbojet engines are more susceptible to damage from small pellet impacts than are fanjets.

(d) Some small objects can cause unacceptable damage to first stage fan blades, although outside of general limits the sizes are undetermined.

(e) Individual pebble (less than 1/4 inch in diameter) impacts into an engine are not likely to cause severe damage in the compressor stage of fanjets; but extensive pebble ingestion will cause erosion and damage to the compressor stage.

(f) The FAA 1/4 inch gravel ingestion test is the only engine requirement to survive FOD that is close to the interest of this study. If we assume that military engines are as survivable as commercial engines certified by the FAA as meeting all parts of AC 33 B-1, it would not be necessary to sweep rock material less than 1/4 inch.

(g) Since engines are not tolerant of large metal objects (reference FAA circular and damage to blades by a 1 gram steel ball), but are tolerant of some metal objects (7 gram titanium shards), some bomb fragments must be swept.

d. Aircraft Design in the Presence of FOD

Typical aircraft modifications to reduce FOD damage are:

(1) Blowaway jets,

(2) Deflectors on tires particularly nose gear,

(3) Removal of fragile antennas,

(4) Installation of heavier skins in some locations, and

(5) Installation of metal shields to cover hydraulic lines and other components in wheel wells.

2. RECOMMENDATIONS

The conclusions and data presented in this study indicate that any comprehensive, analytic treatment of FOD, in the context of the interests in this report, would require a rather large undertaking. Moreover, the amount of systematized, experimental data is extremely lacking. Therefore, the recommended actions display a two-phase approach. The first phase attempts to collect and systematize experimental data that are easily and economically collected. This improved set of facts which can be fitted into the qualitative framework of the effort reported herein will provide a better basis for defining a systematic approach to developing analytic tools for FOD prediction.

A testing program should be established to determine the following, in descending order of priority, for the mission aircraft to be operated from unconventional and bomb damaged airfield surfaces:

a. The tire spray distribution pattern in terms of debris size, shape, weight, and velocity on various surfaces,

b. The effectiveness of deflectors in limiting the tire spray,

c. The probability of engine ingestion of tire sprayed debris,

d. The probability of engine ingestion of debris as a result of inlet vortex formation and engine airflow,

e. The effectiveness of vortex suppression systems in reducing engine ingestion of debris, and

f. The size and composition of debris that can be tolerated by engines.

Some of the agencies that would be involved in major data acquisition are shown in Table 9. This is an initial assessment based on the information and contacts gained during this study. However, some actions related to testing, should be undertaken on a priority basis. These are briefly listed below.

(1) The NASA tests of the F-14 nose gear should be closely monitored. This will establish some quantitative evaluation of nose gear

TABLE 9. AGENCIES INVOLVED IN FOD TEST AND ANALYSIS.

	ITEM	COGNIZANT AGENCIES	PARTICIPATING AGENCIES
1.	TIRE-SURFACE PRODUCTION PARTICLES	FDL	AFFTC, NASA OF
2.	TRAJECTORIES OF PARTICLES PROJECTED BY TIRES	FDL	NASA
3.	PARTICLES, AERODYNAMICS	FDL	NASA
4.	ENGINE INGESTION FLOWFIELDS	APL, FDL	AEDC
5.	AIRFRAME DAMAGE BY NON METAL-LIC PARTICLES	FDL	
6.	ENGINE SUSCEPTIBILITY TO DAMAGE	APL	AEDC
7.	FOD PRODUCTION BY BDR & ALRS	AFESC	
8.	DEBRIS STRUCTURE	AFESC, AFWL	AFATL

rock deflectors. If possible, tests with the debris expected to be found on bomb damaged runways should be part of the experiments.

(2) A mission test aircraft should be equipped with engine screens and collectors so that taxi tests over crushed stone repairs (with no FOD cover) and debris-laden surfaces can be made. This would be used to obtain a general answer to bounding the problem.

(3) It would be desirable to ascertain whether military engines of the mission aircrafts are as tolerant to the 1/4 inch rock as civilian engines. If so, then some surface debris may be permitted.

(4) Any tests conducted such as the soft soil tests during the Summer of 1981 should be investigated to determine whether they provide data pertinent to the FOD issue. If so, the additional data should be collected. This is to include the systematic collection of data to determine debris distribution from actual explosions.

(5) Some experimental data on the effectiveness of USAF sweepers to remove bomb damage debris should be collected. The degree to which some debris can be removed from spalls or scabs should also be investigated.

The recommended tests are judged to be relatively simple and inexpensive to conduct. As such, they represent the most cost-effective approach to acquiring quantitative information. The degree to which this initial information satisfies the recommended data needs is shown in Table 10. Initially, all data items are covered. Due to the diverse sources of this information, the AFESC integration and synthesis can provide proper insights for future direction.

Collection of some of the above data may establish that minor debris can be tolerated and sweeping limits can be determined. In addition, some observations of the data should permit some quantitatively-based insights to expand the qualitative structure developed herein. With that knowledge, analysis can lead to specific recommendations concerning the need and utility for an expanded test and future analytic developments for a second phase.

Until more quantitative information becomes available, however, the current research would indicate that:

(a) Tire-lofted debris probably represents only a minor hazard to airframes, at least when the constraint of serious aircraft degradation within 2 to 3 missions is applied. A possible exception to this is damage to system components within the aircraft wheel wells, because components of a variety of systems vital to aircraft operations are concentrated in wheel wells for ease of maintenance. The detailed evaluation of this potential vulnerability should be made.

TABLE 10. RECOMMENDATION FOR INITIAL TESTING.

RECOMMENDED PRIORITY DATA	NASA F-14 TIRE TEST	AFESC TESTS	AFESC SYNTHESIS	APL	TAXI TEST	SWEEPER EFFECTIVENESS
• TIRE SPRAY DEFINITION	0		0			0
• DEFLECTOR EFFECTIVENESS	0		0			
• ENGINE INGESTION OF TIRE SPRAY		0	0		0	
• ENGINE INGESTION BY AIRFLOW		0	0		0	
• VORTEX EFFECTIVENESS			0			
• ENGINE DAMAGE			0	0		
• DEBRIS DEFINITION (BASIC DATA AS PART OF EACH OF THE ABOVE)		0	0			0

(b) Proof tests prior to flight may be necessary to evaluate engine degradation. Such tests may also represent an adequate evaluation of whether or not an engine has been too severely damaged to complete its next mission.

(c) A serious threat to all mission aircraft is debris that is thrown up by the jet blast or propeller blast from nearby aircraft. The lofting of debris is considered severe enough, due to potential for rock size and bomb fragments, to preclude formation takeoffs and limit ground operations.

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APPENDIX A

CHECKLIST OF DATA ITEMS
REQUESTED OF EACH CONTACT/INTERVIEWS

APPENDIX A

CHECKLIST OF DATA ITEMS
REQUESTED OF EACH CONTACT/INTERVIEWS

1. DEFINITION OF PROBLEM AREA

    a. Ground-induced FOD

        (1) Taxi

        (2) Run-up

        (3) Takeoff

        (4) Landing

    b. Damage to Mission-Critical Components Obvious By Routine Inspection

    c. Exclusions

        (1) Bird strikes

        (2) Direct weather effects (hail, sleet, etc.)

        (3) Ordnance

        (4) Runway surface roughness

2. DATA

    a. Compended Data

        (1) Formal reports

        (2) Informal reports

        (3) Description

            (a) What

            (b) When

            (c) By whom

            (d) Where

            (e) Availability

b. Expert Opinion

(1) Types of damage

(a) Type of aircraft and configuration

(b) Individual impacts on airframe/engine

(c) Battering of airframe

(d) Erosion of engine components

(e) Damage to stores and external components

(f) Vulnerable areas

(2) Relative severity

(a) Catastrophic

(b) Reduction of component life

(3) Relation of damage of environment

(a) Mode of operation

(b) Material lofted: amount and description

(4) Fixes tried

(a) Deflectors near wheels

(b) Armoring vulnerable components

(c) Adjust air intake and flow patterns

c. Uncompended Data

3. OTHER SOURCES OF INFORMATION

a. General Categories of Data

(1) Tire-ground interaction and how this may produce objects

(2) Means by which objects can become projectiles

(a) Aerodynamic forces

(b) Jet blast

(c) Tire-object interaction

(3) Lethality of projectiles which impact airframe or are ingested by engines

NOTE: BDM wishes to understand the state-of-the-art in terms of information which can help predict results and design surfaces and/or airframes.

APPENDIX B

FACTORS WHICH IMPACT
ON
ENGINE SUSCEPTIBILITY TO FOD

APPENDIX B

FACTORS WHICH IMPACT ON ENGINE SUSCEPTIBILITY TO FOD

1. INTRODUCTION

Because the engine is a critical component which is susceptible to damage by FOD, some additional discussion relative to the factors which may affect its degree of susceptibility to FOD are presented. This qualitative discussion permits a more detailed understanding of the impact of engine design variables on the susceptibility of an engine to FOD. This discussion is based on the material in Reference 5 and as such is based mainly on the turbofan engines with short inlets used on commercial airliners. With respect to mission aircraft, therefore, the discussion is most pertinent to the C-5A, C-141B, and A-10, as well as CRAF aircraft. Due to the military aircraft configurations, however, the engines on military aircraft tend to be further from the ground than those on commercial aircraft designs.

2. DATA

The type of engine data used for analysis is shown in Table B-1. For reference, the values for the JT9D-7 engine are shown. The analysis can provide a good indication of the relative susceptibility between engine types.

3. FOD SUSCEPTIBILITY OF THE FAN

A number of engine design and installation characteristics can readily be identified as having a distinct influence upon the FOD susceptibility of the fan. They are:

a. The product ($n \times N_1$) of the number of fan blades n and the fan rotational speed N_1. In general, the higher the value of this product, the higher the chance for a foreign object entering the engine from the front to hit a fan blade. Assume that the damage potential to the fan is directly proportional to ($n \times N_1$).

b. The quotient (H_{H1}/D_{H1}) of the distance H_{H1} from ground to the bottom of the engine inlet highlight, and the diameter D_{H1} of the engine inlet highlight. For a given engine the closer the engine inlet highlight is to the ground, the greater the chance of foreign objects being sucked into, and doing damage to, the engine. Assume that the damage potential to the fan is inversely proportional to (H_{H1}/D_{H1}), i.e., to (D_{H1}/H_{H1}).

c. The engine inlet highlight area A_{H1}. The larger this area, the greater the chance of birds or other airborne foreign objects being ingested by the engine. Assume that the damage potential to the fan is directly proportional to A_{H1}.

TABLE B-1. MISCELLANEOUS FAN CHARACTERISTICS.

		JT9D-7
1.	NUMBER OF FAN BLADES	46
2.	NUMBER OF BLADE DAMPERS	2
3.	HUB INLET RADIS - IN	17.14 IN
4.	HUB INLET RAMP ANGLE	12°
5.	BLADE ROOT AXIAL WIDTH	5.9 IN
6.	HUB OUTLET RADIUS	18.38 IN
7.	HUB OUTLET RAMP ANGLE	12°
8.	LOCATION OF STACKING AXIS FROM BLADE ROOT FRONT PLANE	2.7 IN
9.	BLADE LENGTH ALONG STACKING AXIS	27.7 IN
10.	TIP CLEARANCE AT STACKING AXIS	.16 IN AVG.
11.	TIP INLET RADIUS	45.9 IN
12.	TIP INLET CASE ANGLE	15°
13.	TIP OUTLET RADIUS	45.2 IN
14.	TIP OUTLET CASE ANGLE	15° IN
15.	CHORD (@ R=...) - ROOT	6.00 (19.00) IN
	CHORD (@ R=...) - MEAN	6.69 (32.28) IN
	CHORD (@ R=...) - TIP	9.00 (44.90) IN
16.	MAX. THICKNESS - ROOT	.448 IN
	MAX. THICKNESS - MEAN	.276 IN
	MAX. THICKNESS - TIP	.193 IN
17.	MAX. THICKN/CHORD - ROOT	.075 IN
	MAX. THICKN/CHORD - MEAN	.041 IN
	MAX. THICKN/CHORD - TIP	.024 IN
18.	LEADING EDGE RAD.	
	- ROOT	.025 IN
	- MEAN	.019 IN
	- TIP	.019 IN

TABLE B-1. MISCELLANEOUS FAN CHARACTERISTICS (CONTINUED)

			JT9D-7
19.	TRAILING EDGE RAD.		
		- ROOT	.019 IN
		- MEAN	.013 IN
		- TIP	.009 IN
20.	STAGGER ANGLE		
		- HUB	12°48'
		- MEAN	45°30'
		- TIP	66°09'
21.	CAMBER ANGLE		
		- HUB	
		- MEAN	
		- TIP	
22.	SPACING (@R=...		
		- HUB	2.59 IN
		- MEAN	4.41 IN
		- TIP	6.13 IN
23.	SOLIDITY (@R=...)		
	CHORD/SPACING	- HUB	2.32 IN
		- MEAN	1.52 IN
		- TIP	1.31 IN
24.	RADIUS OF DAMPER LOCATION		31.9 & 41.6 IN
25.	BLADE RETENTION		DOVETAIL
26.	BROACH ANGLE OF BLADE RETENTION		AX-PARALLEL
27.	STAGGER ANGLE OF BLADE RETENTION		12°
28.	BLADE WEIGHT		8.7 LBS
29.	AIRFOIL WEIGHT		6.9 LBS
30.	N_1 - RPM (SLSTO)		3420
31.	RADIUS TO BLADE C.G.		34 IN
32.	AIRFOIL CENTRIF. FORCE		77,956 LBS

TABLE B-1. MISCELLANEOUS FAN CHARACTERISTICS (CONTINUED)

		JT9D-7
33.	CIRCUMF. VELOCITY - FPS	
	@ N_1 (@R=...) - HUB	567.1
	- MEAN	963.4
	- TIP	1340.0
34.	AIRFOIL KINETC ENERGY AT 4	
	(C.G. @ N_1) FT - LB	110,323
35.	POLAR MOMENT OF INTERIA OF LB-SPOOL, IN-LB-SEC^2	1,678.8
36.	POLAR MOMENT OF INERTIA OF SINGLE	
	AIRFOIL - IN-LB-SEC^2	20.66
37.	AIR MASSFLOW - LBS/SEC	1517.5
38.	ENGINE FRONT FLANGE ANNULUS AREA - FT^2	40.51
39.	MASSFLOW/AREA - LBS/FT^2	37.46
40.	NO. OF FAN STATOR VANES,	
	INNER:	88
	OUTER:	108
41.	CORE-FLOW SPLITTER HIGHLIGHT RADIUS	25.55 IN
42.	CORE-FLOW INNER ANNULUS RADIUS	18.54 IN
43.	CORE-FLOW INLET ANNULUS HEIGHT	7.01 IN
44.	DISTANCE OF CORE-FLOW SPLITTER HIGHLIGHT TO	
	FAN BLADE T.E.	1.24 IN
45.	DISTANCE TO OUTER FAN STAT. TO FAN FL. @ MEAN	9.5 IN
46.	FAN CASE FRONT FLANGE INNER RADIUS	46.53 IN
47.	HUB/TIP RATIO AT FAN BLADE INLET	.37
48.	HUB-SECTION PROPERTIES:	
	RINNER - IN	
	ROUTER - IN	
	CHORD - IN	
	MAX. THICKN.	

TABLE B-1. MISCELLANEOUS FAN CHARACTERISTICS (CONCLUDED)

		JT9D-7
49.	DISTANCE OF INNER FAN STAT. TO FAN BL. @ MEAN	1.26 IN
50.	SLANT OF OUTER FAN STATOR VANES	RADIAL

d. The impact velocity v_r of a foreign object relative to the fan blade, i.e., the vector between the axial velocity v_{ax} of a foreign object and the tangential velocity of the fan blade (for example, at the blade mean radius). Assume that the damage potential to a fan blade is directly proportional to the kinetic energy of a foreign object relative to the fan blade, i.e., to v_r^2.

e. The blade bending stress factor f which reflects the magnitude of maximum bending stress occurring near the blade root during foreign object impact. This factor f is primarily a function of (blade aspect ratio)$^{1.1}$, (the exponent 1.1 being applicable to the aspect ratios under consideration). Assume that the damage potential to a fan blade is directly proportional to f, (this neglects the beneficial influence of the blade damper shrouds upon blade-bending stresses).

f. The axial velocity v_{ax}^* of a foreign object at which it theoretically could pass through the flow passage between two adjacent and rotating fan blades without touching the blades (for example, at the blade mean radius). Of primary practical interest is the minimum axial velocity at which a particle can travel untouched through a blade passage. This velocity is the one that lets a particle, which enters the flow passage on the suction side of the leading edge of a rotating airfoil, pass through the passage and just clear the pressure side of the trailing edge of the succeeding blade. Assume that the damage potential to the fan is directly proportional to the ratio (v_{ax}^*/v_{ax}), where v_{ax} is the axial velocity of a foreign object or particle.

Thus, a relative fan blade damage potential DF can be defined as:

$$D_F \sim (n \times N) \times (D_{N1}/H_{H1}) \times A_{H1} \times v_r^2 \times f \times (v_{ax}^*/v_{ax})$$

and this can be applied to engines, normalizing the results with respect to the engine with the lowest D_F.

4. FOD SUSCEPTIBILITY OF ENGINE CORE

Some engine design and installation characteristics which have an influence the FOD-ingestability into, and damage potential to, the core. They are:

a. The quotient (A_{Cf}/A_{H1}) of the core-flow inlet annulus area A_{Cf} and the engine inlet highlight area A_{H1}. Assume that the potential of foreign objects being ingested into the core is directly proportional to (A_{Cf}/A_{H1}).

b. The minimum axial velocity v_{ax}^* of a foreign object at which it theoretically could pass through the flow passage in the hub region between

two adjacent and rotating fan blades without touching the blades. The lower v_{ax}^* is required to be for a particle to pass through this blade passage, the greater chance it will have to enter the core-flow annulus. Assume, therefore, that the potential of foreign objects entering the core is inversely proportional to v_{ax}^*, i.e., to $(1/v_{ax}^*)$.

c. The centrifugal gun effect that centrifuges a foreign object along the pressure surface of a blade radially ΔR outward and imposes a radial velocity vector v_{rad} upon it and the axial distance d_{ax} of the core-flow annulus inlet highlight from the trailing edge of the fan blades. The stronger the centrifuging effects ΔR and v_{rad} and the larger the distance d_{ax}, the lower becomes the chance of foreign objects entering the core-flow passage. We call the core-flow annulus area which will still be exposed to foreign object ingestion ΔA, and assume that the potential of foreign objects entering the core is proportional to $(\Delta A/A_{Cf})$.

A relative core passage damage potential can be defined as:

$$D_c \sim (A_{Cf}/A_{H1}) \times (1/v_{ax}^*) \times (\Delta A/A_{Cf})$$

5. OTHER FACTORS

In addition to the above described characteristics which can readily be numerically appraised, several other aspects help assess the susceptibility of an engine to FOD. They are:

a. The sum of LP- (or IP-) compressor plus HP-compressor stages. The fewer stages there are, the less damage-exposure there is.

b. The sum of LP- (or IP-) compressor plus HP-compressor airfoils (rotor blades plus stator vanes, excluding fan). The fewer airfoils there are, the less damage-exposed airfoils there are.

c. The number of variable-geometry compressor stator stages. The fewer variable stages, the less the potential for damage resulting from foreign object ingestion (momentary stator vane-to-rotor blade interference; variable-vane mechanism permanent distortion, resulting in mechanism jamming and/or off-schedule vane angles).

d. The number of variable-geometry compressor stator stages where the variable stator vanes have no inner support shroud; i.e., they are cantilevered from the outside. Unsupported stator vanes are more apt to bend under foreign object impact and interfere with the rotating blades than internally-supported or noncantilevered vanes.

e. The number of fixed-geometry compressor stator stages where the fixed stator vanes have no inner support shroud, i.e., they are cantilevered from the outside.

f. The LP-compressor bleed arrangement, e.g., the on-off 3.0-bleed ring-valve of the JT9D-7, or open-splitter-type bleed passage of the CF6-6, or the modulated twelve-bypass-door configuration of the CF6-50. Each of these bleed arrangements probably has its specific behavior under foreign object ingestion.

g. The meridianal profile and the anti-icing provisions of the fan spinner. Again, the chances are that each spinner has its specific effects upon foreign object impact and subsequent ingestion into the engine. For example, it is known from GE and CFM-International icing tests on CFM56 spinners that conical (pointed) spinners build up and shed considerably smaller ice deposits than elliptical spinners.

h. The number and location of fan blade stiffeners or dampers (or "mid-span shrouds"). It appears that the reason for the JT9D engine series performing over 21 million engine hours without ever incurring shroud shingling is the two-shrouded fan blade. This design provides excellent resistance against blade bending and shroud shingling during blade tip rubbing or foreign object impact, as well as a favorable distribution of foreign object impact loads over several blades.

i. The fan hub ramp angle. This angle varies from 12^{o} - 26^{o} for typical engines. The larger this angle, the more one might presume non-plastically impacting foreign objects to be rebounded radially outwards and away from the fan hub region and, thus, from the core-flow inlet annulus. This would apply to gravel, hail, ice, and the like.

j. There are probably numerous other factors that influence the susceptibility of an engine to foreign object damage. In particular, the interaction between impacting object and fan blade motion/stresses is affected by:

(1) Fan blade centrifugal stiffening, blade twist and camber, blade retention stiffness and orientation (stagger), and damping characteristics.

(2) Effects of span- and chord-wise distribution of blade thickness.

(3) Ratio of fan blade mass to foreign object mass.

(4) Blade natural frequencies.

k. The shape of and flow-field around a spinner also have a considerable influence upon foreign object trajectories, in particular upon the

amount of particles ingested by the core. Centrifuging of sand and rebounding of gravel are clearly affected by spinner shape and flow-field.

APPENDIX C

AIRPLANE FOD REDUCTION TECHNIQUES FOR OPERATIONS ON GRAVEL RUNWAYS

APPENDIX C

AIRPLANE FOD REDUCTION TECHNIQUES FOR OPERATIONS ON GRAVEL RUNWAYS
(From Reference 4)

1. 727 REQUIREMENTS FOR OPERATIONS ON GRAVEL RUNWAYS

The only 727 modifications mandatory for gravel runway operations are the between-the-wheels gravel deflector on nose and main landing gears and protection of the hydraulic brake tubing on the main gear oleos. These are the only changes necessary for operational safety. The objectives are:

a. To prevent engine ingestion of flying gravel, and

b. To preclude loss of hydraulic brake pressure from abuse by flying gravel.

The following modifications are made to reduce wear and tear from gravel runway operations (Figure C-1):

a. Installation of additional fiberglass reinforcement and addition of a protective metal sheet on the lower surfaces of the inboard portion of the inboard aft flaps,

b. Replacement of lower rotating anti-collision beacon with retractable rotating anti-collision beacon,

c. Addition of teflon polyurethane paint on the lower wing surfaces and on the lower body skin,

d. Installation of heavier skin on tail skid door,

e. Replacement of lower VHF antenna with one having a stainless steel leading edge,

f. Replacement of DME blade antennas with flush antennas, and

g. Replacement of ATC blade antennas with flush antennas.

No modifications are necessary in the vicinity of the engine inlet. The aft mounted engines receive natural shielding from the wing, trailing edge flaps, and body. Service experience has shown that foreign-object-damage (FOD) rates on gravel runways are no higher than FOD rates on paved runways.

2. 727 OPERATIONAL PROCEDURES

The special environment of the gravel runway dictates the following changes in operating procedures and techniques for maximum operational safety and economy in operating 727's from gravel runways.

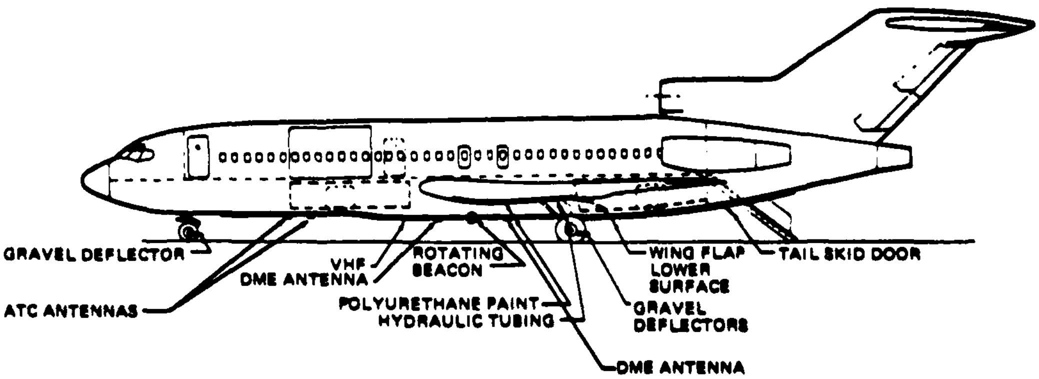

Figure C-1. 727 Gravel Runway Configuration.

a. Reverse thrust of the side engines is limited to idle power. (Full reverse thrust of the center engine is allowed.)

b. Takeoff flap settings are limited to 15° and 25° (5° is not allowed).

c. Air conditioning packs are turned off, and ram air doors are closed for landing.

The reason for the restrictive use of thrust reversers on gravel is that the vertical exhaust of the side engines during reverse thrust could cause gravel ingestion by the engine. Full reverse can be utilized by the center engine at all times because the exhaust is deflected horizontally, leaving the runway surface undisturbed.

The trailing edge flap system at deflection of 15° or more inherently shields the engine inlets from stones thrown back by the main landing gear tires.

The operational changes requiring special control of the air conditioning system during landing will minimize the amount of gravel ingested by ram air scoops at touchdown. This restriction does not apply to takeoff, since flying gravel is prevalent only during tire spin-up at touchdown.

Boeing offers pilot training in short field and unpaved runway operations. Since many gravel runways are short fields, training in short field operation may be desirable for unpaved runway operation.

3. 727 AIRPLANE PERFORMANCE

Increased rolling resistance and lowered surface friction require about 10 percent increase in runway length over the paved runway.

4. 737 REQUIREMENTS FOR OPERATIONS ON GRAVEL RUNWAYS

The 737 airplane must be equipped with a gravel runway kit (Figures C-2) for physical protection of the engines and the aircraft during operations on runways.

The engines are protected by the following:

a. The nose gear gravel deflector (Figure C-2) prevents stones and dirt thrown up by the wheels during takeoff and landing from entering the engines or striking the underside of the airplane. The deflector assembly includes a shield, hydraulic actuator, and a mechanism of load springs and rollers.

The deflector shield is faced with corrosion-resistant steel and has a sheet metal leading edge which acts as a airfoil to provide aerodynamic

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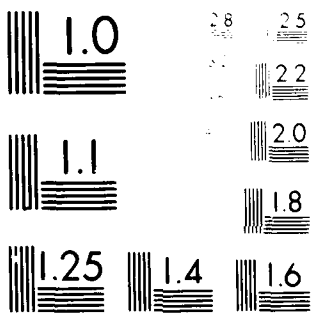

MICROCOPY RESOLUTION TEST CHART

stability to the shield. When the landing gear is in transit, hydraulic pressure is supplied to the actuator, which rotates the deflector shield in relation to the nose gear shock strut. Rotation is programmed to maintain the shield in a nose-up attitude during gear transit.

If hydraulic pressure is lost, the landing gear can be extended manually, and the springs and rollers will properly position the deflector. With either hydraulic or manual actuation of the landing gear, simultaneous positioning of the nose gear gravel deflector occurs. No additional actions are required by the flight crew.

With the gravel deflector installed, the maximum airspeed limit for landing gear operation (V_{LO}) is 180 KIAS. For manual gear extension V_{LO} is 150 KIAS. The limiting speed once the landing gear is fully extended (V_{LE}) is 200 KIAS.

The rollers contact and run on guides in the wheel well to position the shield over the wheel well opening when the gear is retracted. With the gear fully retracted, the nose gear defelctor forms the forward portion of the nose gear door. On the ground, the deflector clears the runway by 3.5 inches during normal taxi operations. This provision allows flat tire clearance.

b. The vortex dissipators (Figure C-2) prevent the formation of air vortices beneath the engine inlets during breakaway at the beginning of taxi and during slow taxi speeds. These vortices, which could conceivably lift dirt or gravel particles upward into the engine, will not form at taxi speeds above 12 knots.

The dissipators use pressure-regulated engine bleed air, discharging it from a boom extending forward from the underside of the engine nose cowl. The air forced downward and aft at pressures up to 55 psig from nozzles on the tip of the boom.

The system is operated by placing the gravel protect switch on the forward overhead panel to ON. This action energizes a solenoid which opens the gravel protection valve on each engine and lets bleed air go through a duct in the nose cowl to the boom below.

The vortex dissipators, which are connected through the squat switch, turn off in flight. Thus, takeoff climb performance is not penalized in gravel operations.

The aircraft is protected from flying objects (Figure C-2) by:

c. Nose gear gravel deflector (described above),

d. Main gear gravel deflector-rubber panel installed between the main gear wheels (Figure C-2),

e. Added antenna protection,

f. Metal shields covering parts of the main gear hydraulic brake lines and the speed brake control cable,

g. Abrasion resistant paint on the lower fuselage,

h. Impact protection for inboard flaps, and

i. Retractable lower anti-collision light installation (Figure C-2).

5. 737 OPERATIONAL PROCEDURES

The following requirements/recommendations are made for 737 unpaved runway operation.

a. The antiskid system must be operable and ON for takeoff and landing.

b. Engine vortex dissipators must be operable and ON for operation on gravel.

c. Use of rudder pedal steering is recommended during taxiing. Make all turns in as large a radius as possible, initiating the turn with rudder pedal steering, to avoid digging in of the nose wheels during the turn. Do not make locked wheel turns. When a 180 degree turn is required on the runway, utilize the entire runway width for the turn.

d. Thrust for taxiing should be kept to the minimum to sustain a slow taxi speed.

e. If the runway is dusty, the airplane should be maneuvered so that the jet blast will not pick up loose debris and so a crosswind will not blow dust back across the runway. To improve visibility, protect the airplane, and avoid engine ingestion of airborne debris, dust should be allowed to settle before starting takeoff roll.

f. Use rolling takeoff procedure if possible. If a stop is required or the airplane is inadvertently stopped before starting takeoff, prolonged static operation above idle power should be avoided and engine EPR should be limited to 1.4 or below before brake release.

g. On landings, use of autobrake system is recommended (if installed) and use of normal reverse, 1.5 EPR, is recommended. Stow thrust reverser before the airplane slows to approximately 70 knots.

h. On unpaved runways the gravel protect switch must be in the ON or ANTI-ICE/TEST position while the engines are operating. Engine bleed air is not used for air conditioning while vortex dissipators are operating during takeoff or landing on gravel runways. This procedure ensures that

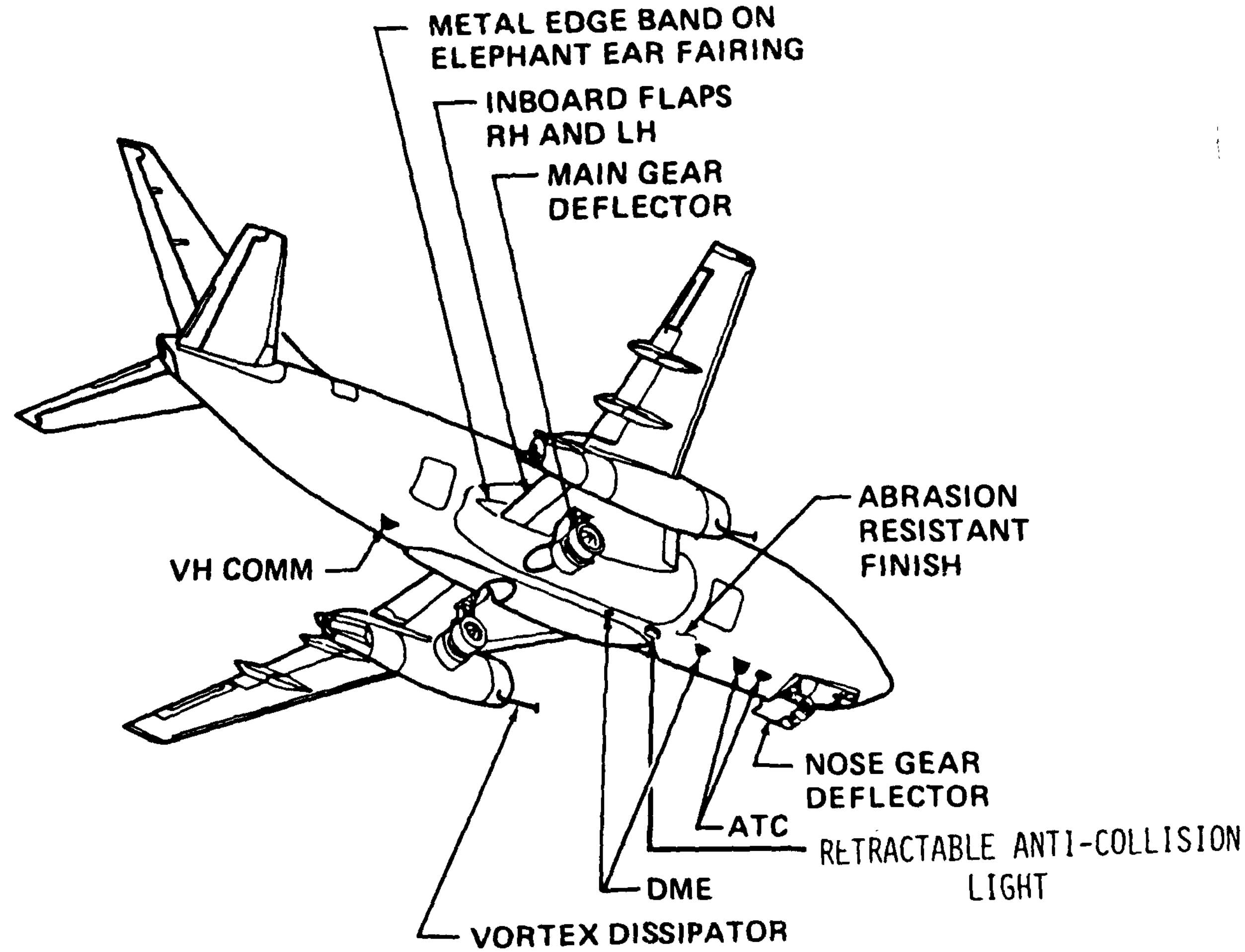

Figure C-2. Gravel Runway Configuration for 737.

dissipator air is maintained at the required pressure. The auxiliary power unit may be used to supply airplane air conditioning while the vortex dissipators are operating.

APPENDIX D

AIRPLANE ENGINE FOD

APPENDIX D

AIRPLANE ENGINE FOD
(From Reference 5)

1. INTRODUCTION

Foreign object damage (FOD) is a key factor in unscheduled engine removals (UERs). Considerable effort has been expended to determine the parameters which affect ingestion of foreign materials so that new airplane design can reduce UERs to a minimum.

Early in 1978, the Propulsion Research group (of the Boeing Airplane Co.) conducted a literature review of FOD related analysis conducted by government and industry as well as the company. The same group also considered parametric correlation of FOD data for inboard wing mounted engines. Results of this study indicated that UERs due to non-bird foreign objects show a trend related to vortex ingestion and nose wheel spray. However, data relative to the L-1011 which became available later in the year did not correlate. This led to the realization that non-bird FOD is both airplane configuration and engine-oriented and cannot be correlated by a single parameter.

Conclusions from the study are:

a. For airplanes using either wing or aft body-mounted engines, non-bird FOD resulting in UER is not a major life cycle cost contributor. Design constraints resulting from non-bird FOD considerations should only be approved on the basis of a cost and safety trade study.

b. Bird strike will account for from 25 to 40 percent of the FOD on a new airplane with wing mounted engines.

c. A significant decrease in non-bird FOD will result from use of blow-away vortex dissipators.

d. Engine configuration plays a significant role in UERs due to foreign object ingestion.

2. FOREIGN OBJECT INGESTION REQUIRING IMMEDIATE ENGINE REPAIR

Engine damage caused by ingestion of foreign material is dependent on:

a. Availability of foreign material of such a nature as to cause damage

b. Some hardware characteristic or mechanism which will result in ingestion of the foreign material

c. Engine tolerance to ingested foreign objects

In the case of non-bird foreign objects, the material may be available because of airport location, airport housekeeping and maintenance philosophy, airline maintenance practices and mechanic care, and airplane design practices. In the case of birds, availability of foreign material will result primarily from airport location and procedures used to discourage bird population.

Mechanisms resulting in ingestion and degree of damage sustained may include wind, spray from wheels and flaps, debris blown about by the engine exhaust during taxi and lineups, reverse engine exhaust, vortex action during static or flow moving engine operation, airplane speed, airplane and engine noise signatures, engine frontal area, engine air utilization, and engine structural and aerodynamic characteristics.

(1) Ingested Objects

The various sources and causes of engine FOD identified above may result in ingestion of foreign objects ranging from fine particles of sand to objects as large as the nacelle diameters.

Ingestion of foreign objects results in one of three degrees of engine damage:

(a) Structural damage requiring unscheduled ergine (UER) or module removal for direct shop maintenance or replacement

(b) Nicks, dents, etc., which require on wing blending or other line maintenance

(c) An increase in exhaust gas temperature (EGT) and thrust specific fuel consumption (TSFC), due to erosion of compressor and turbine blades and vanes by small hard foreign objects, resulting in early engine overhaul

Foreign objects resulting in UERs generally pass through the engine core. When this occurs, identification of the object is sometimes impossible, and it is therefore identified in statistical data as "unknown object." Some cbjects large enough to result in an UER through the core, lodge in the compressor, burners or turbine, and can be identified. Table D-1 is a list of the foreign objects which resulted in UERs during 1975 on airplanes powered by Pratt and Whitney JT3D and JT8D engines. Bird ingestion can usually be determined by the remains found in or on the engine. Therefore, the number of bird strikes reported is assumed to be the total bird strikes which resulted in UERs. Note from Table D-1 that the 58 to 87 percent of the reported FOD causing JT8D UERs resulted from "unknown objects," depending on aircraft type. Bird strikes account for from less than 1 percent to 37 percent, depending on airplane type.

TABLE D-1. FOREIGN OBJECTS RESULTING IN UNSCHEDULED ENGINE REMOVAL (NUMBER OF INCIDENTS).

(DATA PROVIDED BY PRATT & WHITNEY)

	JT8D		
	POSITION		
727	1	2	3
BIRD STRIKE	4	0	2
ACFT TIRE	5	0	3
HARD OBJECT	1	1	3
ICE	2	0	2
STEEL OBJECT	1	0	1
BOLT/NUT/SCREW	1	1	0
FIRE EXTINGUISHER	0	0	1
CLOTH/SOFT OBJECT	1	0	1
WRENCH	1	0	0
SILICA GEL BAG	0	1	0
UNKNOWN OBJECT	59	30	49
737			
BIRD STRIKE	19	20	
HARD OBJECT	0	1	
STONES	1	1	
ACFT TIRE	0	2	
METAL	0	1	
THERMOMETER	1	0	
BOLT/NUT/SCREW	1	0	
UNKNOWN OBJECT	30	30	
DC-9			
BIRD STRIKE	8	2	
BOLT/NUT/SCREW	2	2	
ACFT PART	1	1	
ACFT TIRE	4	9	
STONES	0	2	
ICE	1	3	
FLAP ACCESS COVER	1	0	
UNKNOWN OBJECT	73	68	
CARAVELLE			
BIRD STRIKE	1	0	
ACFT TIRE	0	1	
UNKNOWN OBJECT	5	1	
MERCURE			
UNKNOWN OBJECT	1	1	

	JT3D			
707	1	2	3	4
BIRD STRIKE	2	0	2	1
BOLT/NUT/SCREW	0	1	0	0
CEMENT	0	0	0	1
UNKNOWN OBJECT	15	11	10	11
DC-8				
BIRD STRIKE	1	0	2	6
ACFT TIRE	0	1	0	0
THROAT MIKE	0	0	1	0
UNKNOWN OBJECT	7	9	7	4

Table D-2 presents similar data for the JT9D engine. Over seven hundred ingestion incidents resulting in engine damage occurred during the six and one-half years of this data sample. Of the total, 353, or 49 percent, of the objects causing damage could not be identified. Bird strikes account for 298, or 41 percent. None of the remaining identified objects accounted for more than 3 percent of the total. Since the mechanism of ingestion is different for non-birds and birds, each is handled separately.

When the non-bird ingested objects cause minor damage resulting in "on wing" blade blending, not only is the object normally unidentified but details of the occurrence are seldom reported. Since no informative data is available, the largest segment of potential statistical data is unavailable for study. The cost of "on wing" blade blending repair is included in line maintenance costs. These costs are comparatively minor. However, the resulting schedule delays generate ill will by the traveling public, and this type of FOD problem is a concern to the airlines.

(2) FOD Due to Objects Other Than Birds

Because of the differences in route structure and because the vast majority of FOD is known to occur while the airplane is on or near the airport, all FOD comparisons are based on engine cycle rather than engine hours. Table D-3 is a composite of the data extracted from Vol. 2 (Reference 5), Para's 2, 3, and 4, relating to removals per engine cycle. The data relative to the DC-10 airplane are included, because they are more definitive than that received from General Eelctric. Data which identifies FOD occurrences by engine position is shown in Table D-4. Corrections suggested to an earlier Boeing report were applied by Boeing and were included in the data reported in Table D-4. Table D-5, taken from Pratt and Whitney data found in Para. 4.1, Vol. 2, for the JT9D engine provides a breakdown of the FOD occurrences. The breakdown includes reported ingestion resulting in unscheduled engine removals (UERs), in-flight shut down (IFSD), airplane turn back (ATB), and incidences which resulted in on wing module or blade replacement (OWR), blade blending or no damage (ND). In some instances, an occurrence which resulted in an IFSD may also have resulted in an ATB and UER. If an IFSD resulted in a UER, it is not recorded as an IFSD. These data show that module or blade changes (OWRs) were involved in 179 (25 percent) of the reported FOD occurrences. Minor damage occurred in 136 (19 percent) of the reported occurrences. In the remaining occurrence, the engine was damaged to an extent requiring engine removal.

Engine mode was also considered with the JT9D data. Engine mode at the time of occurrence was identified in 207 of the 721 occurrences. These data are shown in Table D-6. Only 50 non-bird occurrences were found. The data shows that observed non-bird ingestion occurred about equally at all engine modes except takeoff, where 15 (30 percent) were noted.

TABLE D-2. FOREIGN OBJECT DAMAGE TO JT9D RESULTING IN UER (NUMBER OF INCIDENTS).

	ENGINE POSITION				
	1	2	3	4	UNK
UNKNOWN	82	94	70	87	20
BIRDS	76	60	82	72	6
ICE	5	5	3	11	4
DIRT & STONE	2				
SNOW & ICE		1	1	4	
ELEC. WIRE		1			
COWL BOLT	1	2			
RIVETS		3	3	1	4
WASHER, BOLT	2	1	4		1
DISK FRAGMENT					1
BAGGAGE CONTAINER				1	1
A/C COWLING	1	1	1	2	1
TIRE		3	2		
COVER				1	
MACHINING DEBRIS			1		1
10 # MAUL	1				
A/C LINKAGE			1		
NUTS	2				
A/C WHEEL				1	
ASPHALT		1			
NON ENG. RIVET		1			
GROUND EQUIP.		2			
WIND SOCK			1		
SOFT OBJECT	1			1	
TREE		1			
PIECE OF WOOD				1	

TABLE D-3. COMPOSITE FOD DAMAGE TO ENGINES BY AIRCRAFT TYPE (REMOVALS PER 1000 ENGINE CYCLES).

AIRPLANE	EXCLUDING BIRD STRIKE						INCLUDING BIRD STRIKE						BIRD STRIKE					
	1971	1972	1973	1974	1975	AVE.	1971	1972	1973	1974	1975	AVE.	1971	1972	1973	1974	1975	AVE.
707	.046	.065	.060	.068	.052	.058	.061	.075	.069	.077	.058	.068	.015	.010	.009	.009	.006	.0098
DC-8	.020	.018	.020	.038	.029	.025	.034	.026	.033	.048	.038	.0358	.014	.008	.013	.010	.009	.0108
727	.027	.026	.032	.029	.022	.027	.028	.029	.034	.030	.023	.0288	.001	.003	.002	.001	.001	.0016
737	.061	.039	.036	.036	.033	.041	.070	.052	.055	.047	.051	.055	.009	.013	.019	.011	.018	.0140
DC-9	.052	.050	.070	.052	.039	.052	.055	.053	.072	.055	.041	.055	.003	.003	.002	.003	.002	.0026
747	.044	.116	.141	.064	.061	.084	.070	.146	.152	.079	.083	.106	.026	.030	.011	.015	.022	.0208
DC-10*							0	.066	.028	.116	.157	.092						

*MAJOR U.S. AIRLINE DATA

TABLE D-4. FOD OCCURANCES BY ENGINE POSITION
(RATE PER 1000 ENGINE HOURS)

	Eng. Pos.	FOD (Excluding Bird strikes)*				Bird strikes**			
		1971	1972	1973	1974	1971	1972	1973	1974
707 (JT3D)	#1	.024	.024	.024	.024	.004	.004	.004	.040
	#2	.016	.020	.016	.024	.004	.004	.004	.004
	#3	.012	.024	.024	.024	.008	.004	.004	.000
	#4	.012	.016	.020	.024	.008	.004	.004	.004
720 (JT3D)	#1	.004	.000	.000	.020	.000	.000	.000	.000
	#2	.000	.004	.008	.020	.000	.000	.000	.004
	#3	.004	.024	.000	.012	.004	.000	.000	.000
	#4	.024	.016	.004	.012	.004	.004	.000	.000
DC-8 (JT3D)	#1	.008	.008	.004	.008	.004	.004	.008	.000
	#2	.008	.008	.008	.020	.008	.004	.004	.004
	#3	.008	.008	.008	.016	.004	.004	.008	.004
	#4	.004	.008	.012	.016	.004	.008	.004	.004
727 (JT8D)	#1	.027	.015	.033	.030	.003	.003	.003	.000
	#2	.012	.015	.015	.012	.000	.000	.003	.000
	#3	.033	.033	.036	.036	.000	.000	.003	.003
737 (JT8D)	#1	.092	.052	.056	.040	.008	.022	.020	.008
	#2	.060	.046	.028	.046	.014	.012	.024	.006
DC-9 (JT8D)	#1	.056	.070	.092	.068	.004	.004	.004	.004
	#2	.066	.052	.078	.058	.006	.006	.002	.002
747 (JT9D)	#1	.032	.028	.040	.012	.008	.008	.004	.004
	#2	.016	.040	.140	.016	.008	.008	.000	.004
	#3	.004	.032	.028	.020	.004	.008	.004	.004
	#4	.004	.028	.040	.020	.004	.008	.004	.004

* Premature engine removals for FOD (excluding bird strikes) per 1,000 engine hours.

** Premature engine removals due to bird strikes per 1,000 engine hours.

TABLE D-5. JT9D INGESTION OCCURRENCES (1971 THROUGH MAY 1976)

TOTAL	UNKNOWN OBJECT	BIRDS	ICE	NUTS & BOLTS	RIVETS	PANEL OR PAIRING	STONE & DIRT	TIRE	OTHER
UER	236	89	8	16	2	3	2	3	12
IFSD	2	27	1	1					
ATB		4							
MD	55	77	4						
OWR	60	101	6	1	2	1	—	—	8
	353	298	19	18	4	4	2	3	20

TABLE D-6. ENGINE MODE WHEN HIT IDENTIFIED JT9D/747 (1970 THRU MAY 1976).

ENGINE MODE	BIRDSTRIKES	OTHER
STARTUP	1	1 (a)
GROUND	0	5 (a, a, b, c, d)
TAXI	3	5 (e, e, e, f, a)
TAKEOFF	103	15 (8 g's, h, h, i, j, j, k, l)
CLIMB	20	6 (5 g's, k)
CRUISE	2	4 (g, g, g, h)
APPROACH	13	2 (e, m)
LANDING	15	6 (g, g, g, h, j, n)
REVERSER	0	6 (5 h's, o)

a) Ground Equipment
b) Elec Wiring
c) A/C Sheet Metal
d) 10 lb Maul
e) Rivets
f) Wind Sock
g) Unknown
h) Ice
i) A/C Wheel
j) Tire
k) Bolt
l) Nut
m) Tree
n) Wind Sock
o) Stones

Table D-3 data for non-bird related UERs are plotted in Figure D-1. The data are relatively consistent between years for the 707, DC-8, 737, DC-9 and 727 airplanes since they had a comparatively large data base established prior to 1971. The data sample is much smaller and the data show larger variations between years for the 2nd generation 747, DC-10 and L-1011 airplanes. Data for these airplanes gain consistency with time which indicates that the data base is becoming statistically adequate. Although yearly comparisons cannot be made for the above reason, it is believed that comparisons based on the averages over several years are valid. Several facts can be derived from Figure D-1. First, there does not appear to be a clear FOD advantage for aft body-mounted engines. Although the UER rate for the 727 is low, it is still slightly higher on average than the DC-8. The opposite is true for the DC-9 which has a UER rate significantly higher than the 737 but lower than the 707. Second, the rate of UERs for the 707 is greater than the rate for the DC-8 by an average factor of 2.4. Third, the UER rate for the L-1011 is significantly less than the rate for other second generation high-bypass-engined airplanes. From Table D-4, it is evident that engine position on underwing engine installations is not a significant parameter. On average, the 707 and 747 outboard engines have a slightly higher UER rate than the inboard engines, while the DC-8 shows a slightly higher inboard UER rate compared to the DC-8 outboard engines.

3. FACTORS AFFECTING ENGINE FOD

Additional data and speculation as to the reasons for the above observations are provided in the following paragraphs.

a. Aft Body-Mounted Engines

Two theories exist to explain the FOD which occurs to aft body mounted engines. One theory is that the reversers cause loose material to be blown forward, striking the flaps and being deflected into the engines. The second theory is that the main landing gear which are in line with the engine, kick up material which is flung on a trajectory such that it is ingested by the engines. Early Boeing studies relative to the 727 recognized these two potential mechanisms and flap settings were established for both takeoff and landing to reduce the amount of engine FOD. Volume 2 (Reference 5), Paragraph 2.3, is a very recent communication from a major airline which indicates that even today there is no clear definition of the relative importance of the two theories. The airline has found through inspection and analysis that most of the damage to the 727 and DC-9 engines is caused by unknown hard objects believed to be rocks or small solid metal parts of from 1/4 to 1/2 inch. By deduction, this airline engineering department concludes that the ingestion occurs either during reverser action below 70 knots or during takeoff roll due to tire kickup. They currently lean toward thrust reverser action as the major cause, because of a Douglas test film which showed colored pieces of chalk bouncing off the DC-9 flaps during actual thrust reverser use at speeds below 70 knots. Yet, it is suggested in their report that a reason for the

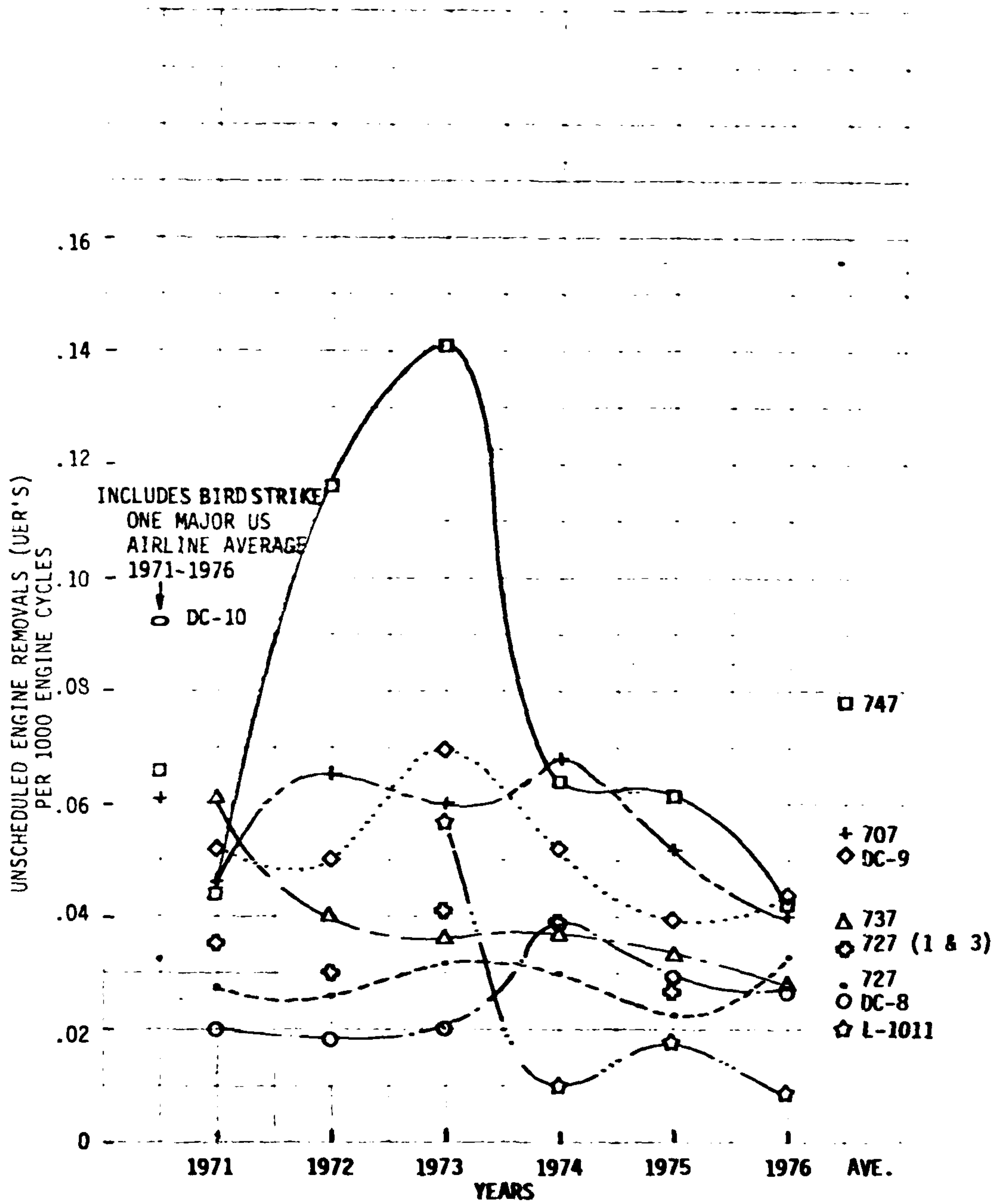

Figure D-1. Data Plot for Non-Bird Related Unscheduled Engine Removal.

higher DC-9 UER rate than the 727 UER rate is that the DC-9 engines are lower with respect to the main gear, which places them in a better position to catch material kicked up by the tires. Of the known ingested objects resulting in UER, aircraft tire pieces are highest for both 727 and DC-9 (see Table D-1). It is not known at what point in the takeoff or landing cycle that ingestion occurred.

b. Wing-Mounted Engines

Foreign object damage is a factor in new airplane design relative to engine position. Because they are closer to the ground and because of the possibility of nosewheel spray, it would seem, that underwing-mounted engines would be most susceptible to non-bird FOD and that on our engine models the inboard engines would be more prone to FOD than the outboard engines. However, it has previously been shown in this document that aft body-mounted configurations are not necessarily less prone to non-bird FOD. Further, Table D-4 data indicates that on four engine configurations the outboard engines sustain FOD rates which result in UERs that are as high or higher than inboard engine rates. Paragraph 4.1 in Vol. 2 (Reference 5) received from Pratt and Whitney relative to the JT9D engine, identifies over 700 FOD occurrences between 1970 and May of 1976. The non-bird portions of the data are shown in Figure D-2.

Figure D-2 shows that the number 2 inboard engine has the highest total number of non-bird FOD occurrences. However, the sum total occurrences on the outboard engines are slightly higher than the sum total occurrences on the inboard engines. It is also evident that the number 3 inboard engine has the lowest FOD rate. Note also that the low number 3 engine FOD is primarily a result of low fan damage only. Since the relationship of the inboard engines to the nosewheel and to the outboard engine, including the thrust reversers, is completely symmetrical, it is difficult to explain the inboard engine fan damage differences. One possibility involves the direction of rotation of the engines. Assume that foreign objects resulting from nose wheel spray and from air flow displaced from the fuselage, etc., approach the lower part of the inboard nacelles from different angles. If the direction of blade motion at the lower part of the nacelle is clockwise, it is clear either intuitively or by drawing vectors that particles approaching the bottom of the number 3 nacelle from the right hand side have a greater probability of passing through the blades without impact than particles approaching the number 2 engine from the left hand side. Since both the JT9D and the CF6 engines rotate clockwise as viewed from the rear, one should expect a higher rate of impacts on the number 2 engine than on the number 3 engine for airplanes using these engines. Data shown in Figure D-2 for the 747 agrees with the premise. Data broken out by engine position was not available for the DC-10. However, data for the RB211 engines installed on the three engine L-1011 airplane indicates that non-bird FOD occurs more often on the number 3 engine than on the number 1 engine. Again, this verifies the premise, since the direction of rotation of the RB211 engine is opposite the JT9D and the CF6 engines. From Figure D-2, it appears that on the 747

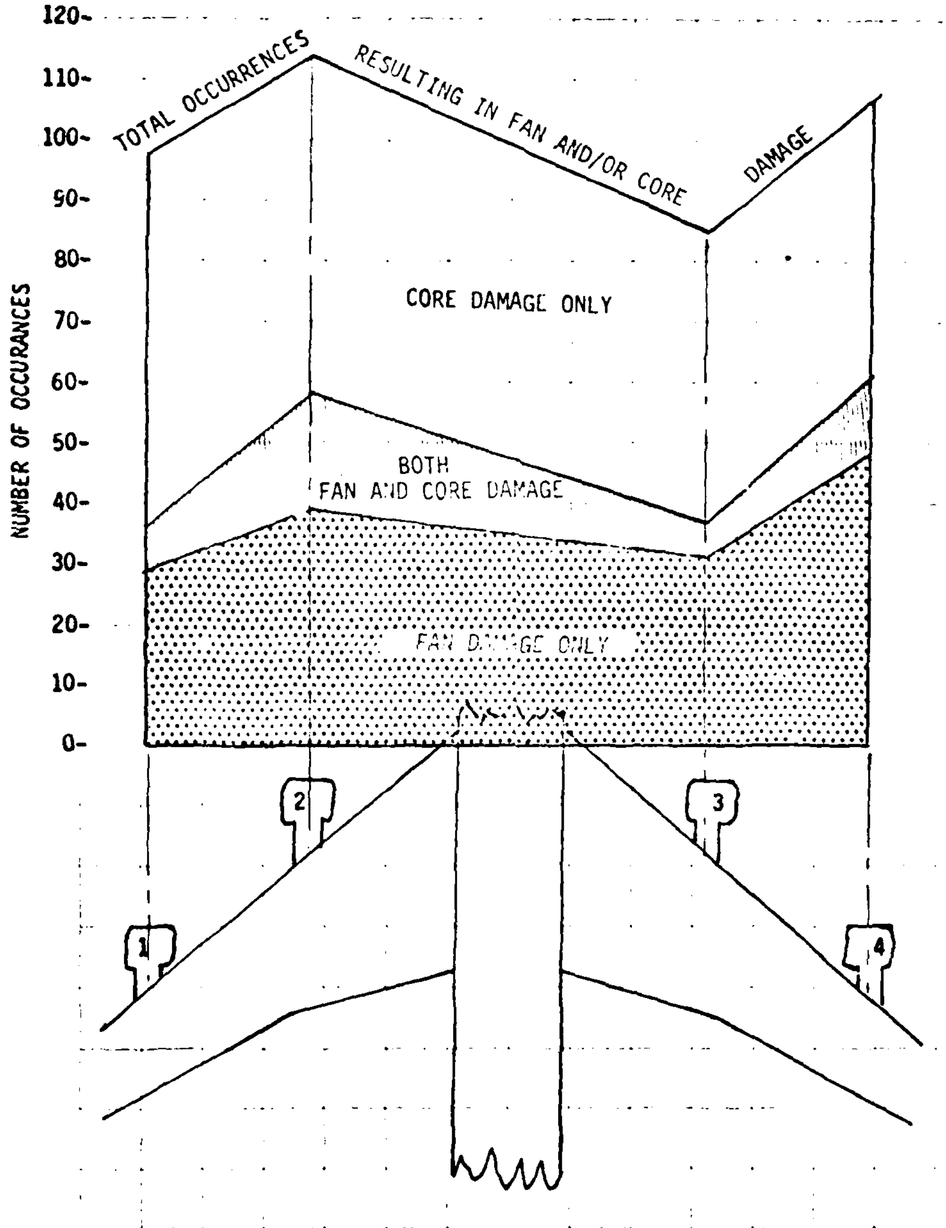

Figure D-2. Non-Bird FOD Occurrences.

airplane the total number of non-bird FOD occurrences is approximately the same for the number 1 and 4 outboard engines.

It has been suggested that the reasons for the outboard engine FOD rates are: runway debris kicked up by the inboard engines during reverse thrust and/or that the outboard engines may extend over the unimproved portions of taxiways or the dirtiest sections of the runways. However, the same FOD relationships between engines holds for the 707 whose outboard engines are approximately 18 feet closer to the airplane centerline than the 747 outboard engines. This fact suggests that engine overhang is probably not the answer. Thrust reverser action may be a cause. However, of the over 700 JT9D occurrences, only 6 are known to have occurred during thrust reverser operation and another 21 occurred at some point during landing.

The data shown in Figure D-2 is also interesting in that it is apparent that over 50 percent of the non-bird FOD occurred in the core only. That is, either the foreign object which resulted in core damage originated aft of the fan or passed through the fan without causing reportable fan damage. A third possibility is that the core damage was a result of a core component failure rather than foreign object ingestion. Since the "core damage only" occurrences are essentially the same for all engine positions, it is possible that a percentage of so-called non-bird FOD is really a result of component structural failure.

The parameter H/D (engine height from ground directed by engine hilite diameter) does not appear to be a satisfactory method of establishing engine distance from the ground where UERs due to FOD is concerned. For instance, two relatively recent reports (see Volume 2 (Reference 5), Para's 5.5 and 5.6), conclude that H/D should be limited to 0.6 and 0.5, respectively. The first report used a data base going through 1974, while the second used a data base through mid-1976. This may explain the difference in their respective conclusions. Figure D-1 shows that since 1974 the UER rate due to non-bird FOD is essentially the same for the 707 and 747. Yet the 747 H/D = 0.6 while the 707 H/D = 0.8. Again, the non-bird UER rate for the 747 and DC-10 wing-mounted engines are comparable, yet the DC-10 H/D is less than the 747. The DC-10 and L-1011 H/D is approximately the same for each airplane, yet the UER rate for the L-1011 is significantly less than the rate for the DC-10. These results imply that while the parameter H/D may be a factor, its value as design criteria is questionable relative to UERs due to FOD.

Results of the tests reported in Reference 2 indicate that small particles such as sand are much more responsive to the parameter H/D than are the larger particles. This factor may be significant relative to erosion. Unfortunately, the author found it impossible to obtain statistical data from operational airlines which could be used to correlate erosion and H/D. Since erosion has been identified as a significant contributor to life cycle cost, a more adequate method of reporting by the airlines and

engine manufacturers is called for to establish the significance of engine location.

c. *Nosewheel Spray*

One of the mechanisms often suggested as a major contributor to inboard wing-mounted engine FOD is object spray caused by the nose gear. Parameters which may affect the spray patterns are airplane speed, number of wheels, type of tire, size of wheel, size of foreign object, amount of foreign objects, and engine relationship to the nose gear. An analysis to evaluate all of these parameters was not within the scope of this study. The following material is presented in an attempt to establish a qualitative comparison of the probability of nose gear object spray between operational commercial transport airplanes based on engine inlet/nose gear relationship.

Studies conducted relative to nosewheel spray are reported in C/S 737-PPU-485 and B-8431-PROP-905 (5.7 and 5.8, Vol. 2 (Reference 5)). C/S 737-PPU-485 reports on tests conducted on gravel during development of the 737 nosewheel gravel deflectors. The tests without deflectors proved that gravel spray from a gravel runway generated by the 737 nosewheel could be ingested by the engines. The highest rate of gravel caught occurred at an angle from the wheel of between 10 and 20 degrees and the number of rocks caught decreased exponentially with height above the ground. Figure D-3, taken from the C/S, indicates the type hardware, conditions and results obtained from the test. Although these test results are not necessarily applicable to a rock or rocks on an improved runway, they do provide a rough idea of what could be expected.

C/S B-8431-PROP-905 is a study applicable to water spray. Figure D-4 of the C/S provides proposed inlet location design criteria for a given tire configuration. The 737, 707, 747, DC-10, DC-8, and L-1011 inlet locations have been superimposed on the C/S figure, and the redrawn result is shown as Figure D-4. By comparing Figure D-3 and Figure D-4, it appears that there is some correlation between water spray and gravel spray. That is, as the angular displacement from the 737 nose gear increases beyond the engine centerline (Figure D-3), the amount of rocks caught decreases very rapidly. This would be similar to increasing the offset ratio S/L (Figure D-4) which indicates that effects of water spray would decrease. Although the areas of acceptability or unacceptability may change with tire type, the relative degree of acceptability between various airplanes, assuming they all used the same tire type, would not likely change.

Results indicate that the 737, DC-10, and DC-8 wing-mounted engines should be more susceptible to nosewheel object spray than would the 707, L-1011 or 747. These results are not in agreement with the statistical data shown in Figure D-1. Therefore, nosewheel spray on current airplanes is not considered to be a major cause of foreign object ingestion, although it is believed to be a contributor.

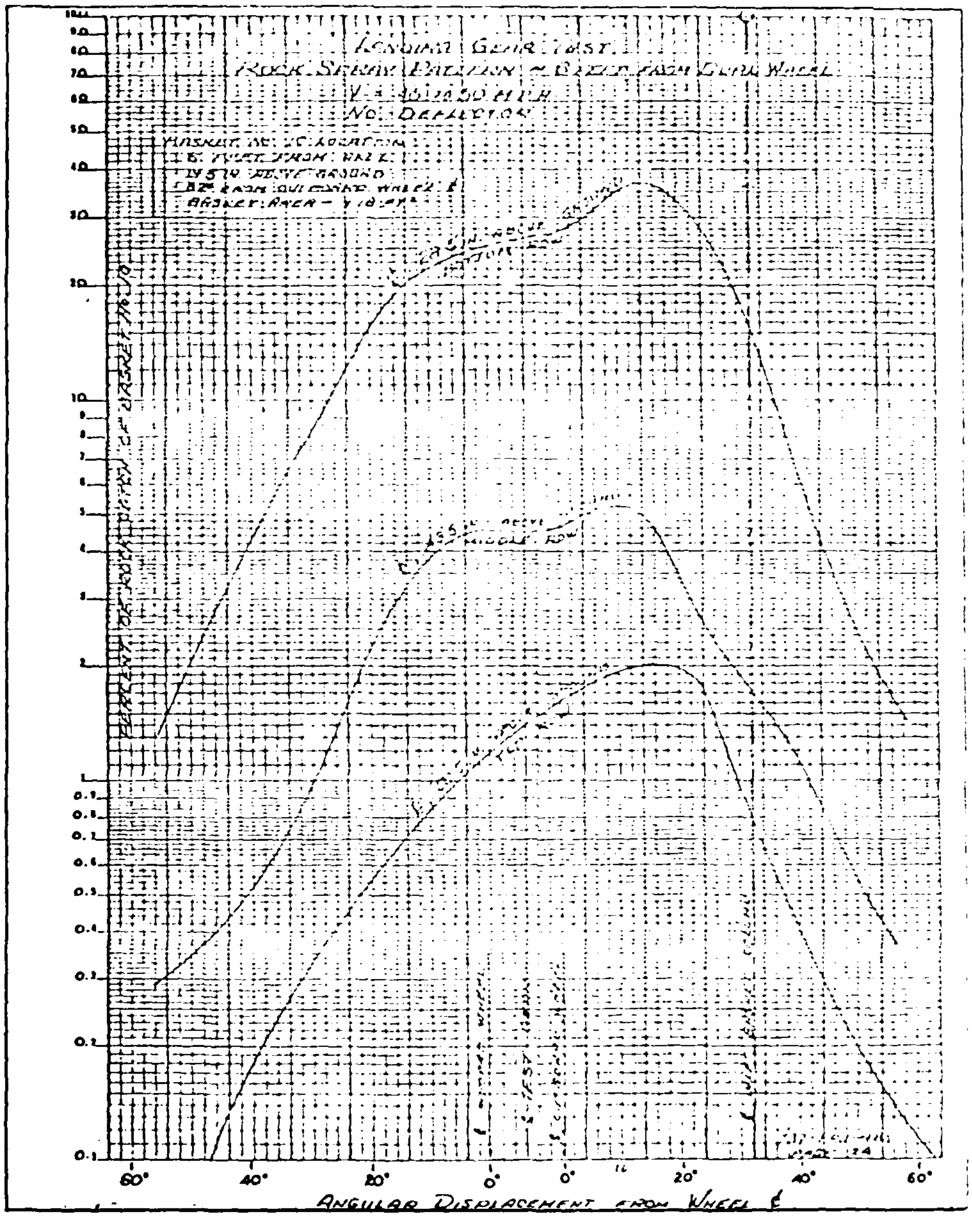

Figure D-3. Landing Gear Test - Rock Spray Pattern.

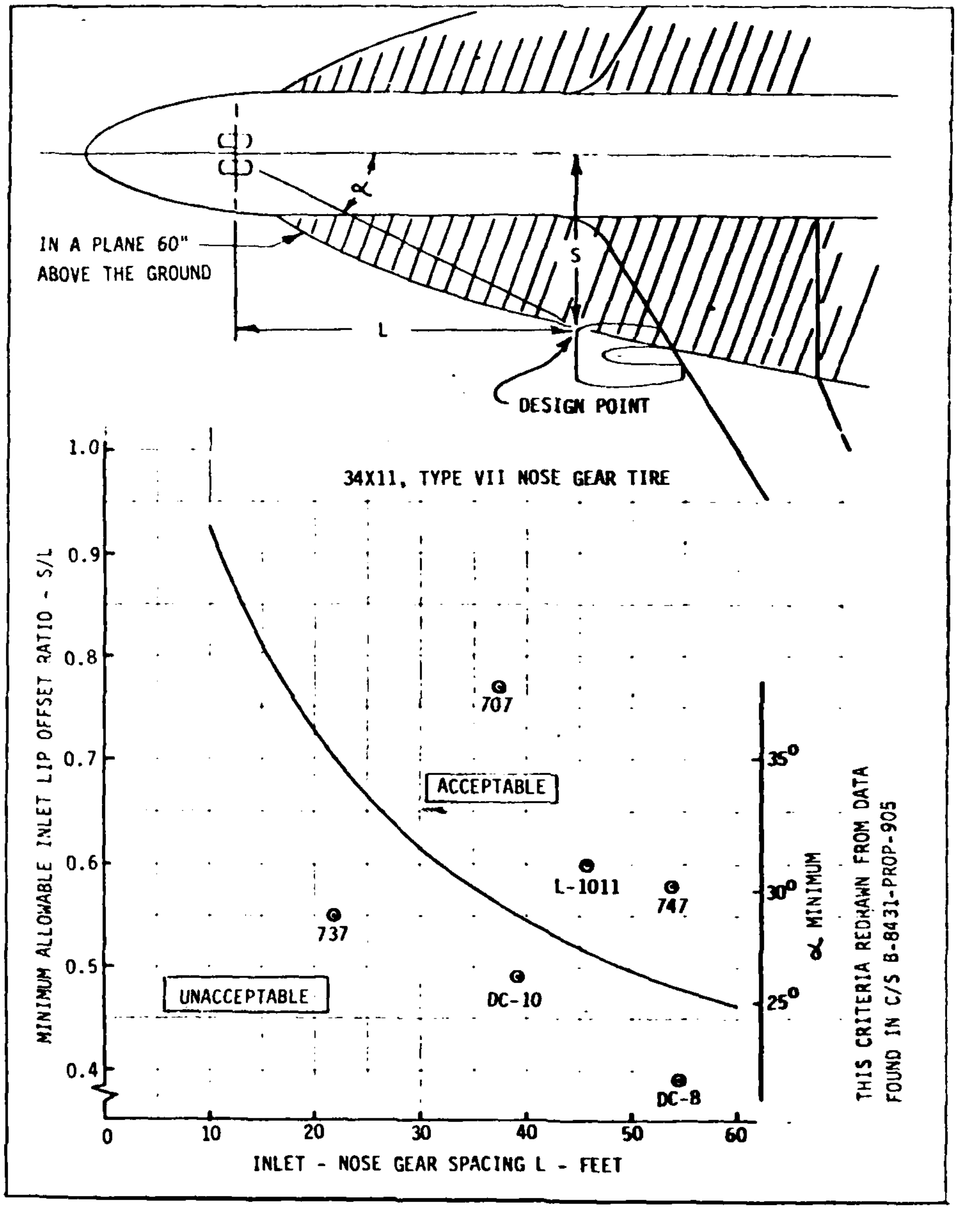

Figure D-4. Nose Gear Water Spray Inlet Location Design Criteria.

d. Vortex Dissipators

Figure D-1 graphically shows that 707 FOD related UER rates are consistently from 1.5 to 3.0 times higher than DC-8 UER rates by year. The DC-8 engine inlet is 90 inches closer to the fuselage center line, 206 inches farther aft of the nosewheel and has about 10 inches greater ground clearance relative to the 707. It is also noted that the 707 is equipped with blow-in doors. Of the various mechanisms previously proposed, only three can explain the DC-8/707 FOD/UER delta: nosewheel spray, vortex action, and thrust reversers. The other mechanisms (wind, line ups, speed, noise signature, frontal area, air utilization, and engine structural and aerodynamic characteristics) are all comparable for both airplanes.

Results relative to nosewheel spray indicate that the DC-8 would be unacceptable under the C/S criteria. The 707 is clearly well within the acceptable range, which indicates that the DC-8 may be more susceptible to foreign objects excited by the nosewheel spray since the 707 outboard engines have a higher FOD rate than the inboard engines. The opposite should be true if blow-in doors increased the probability of foreign object ingestion due to ricochets from the fuselage or main landing gear into the side of the engines. Therefore, the nose wheel can be eliminated as the ingestion mechanism, which would explain the DC-8/707 UER delta.

Thrust reverse may also be eliminated as an explanation, if it is assumed that operators of both airplanes abide by the operational criteria which requires thrust reverse decrease or termination at a speed that eliminates exhaust re-ingestion. Again, the effect of the blow-in doors is unknown. They increase the possibility of object ingestion, since objects could enter the engine from the side or rear. However, in data identified in Table D-6, relative to the JT9D engine, only 12 non-bird FOD occurrences were identified as occurring during landing or reverse thrust operations. Other data also indicate that thrust reverse is not a significant FOD contributor when conducted per the book.

The remaining potential mechanism appears to be related to vortex formation. The DC-8 has incorporated two factors which should provide advantages relative to vortex formation. One factor is that its engines are approximately 10 inches higher above the ground than are the 707s. The second factor is that a large majority of the DC-8s are equipped with vortex dissipator kits. As an example, 100 percent of the two largest US DC-8 fleet operators are so equipped. Relative effectiveness of these factors is difficult to determine from reported data. However, some analytical and test data are available.

A discussion of vortex formation is provided in Reference 2. The summary of the analytical protion of the study is quoted below:

> "Analytical study of the inlet vortex problem is difficult. Although potential flow methods produce results

that appear to possess most of the flow field characteristics, a close study of the region beneath the inlet shows that velocities are not of the needed magnitude or direction to produce ingestion. Viscosity affects only a small portion of the complete flow field but it is primarily responsible for the flow that makes ingestion likely. The inlet vortex impresses a strong pressure gradient on the ground plane boundary layer that causes large radial flows inward in the boundary layer. This secondary low then continues up the core of the vortex toward the inlet. The radial velocities are of the same magnitude as the external tangential velocities and the axial velocities in the vortex core are probably of the same magnitude as the tangential velocities just outside of the core. Since these velocities can be as high as 300 feet per second and the velocity necessary to support a 1/2" diameter particle of specific gravity 2.5 is only 100 feet per second, velocities necessary for ingestion are available through viscous effects. No complete analysis of this region is available at the present time."

Model tests reported in Reference 2 indicate that inlet air flow and distance of the inlet from the ground have an influence on vortex formation and hence on foreign object ingestion. These effects were correlated by H/D where D is the inlet hilite diameter and H is the distance from the ground to the lowest point on the hilite diameter. Data taken from Reference 2 indicates that the effect of H/D dissipates rapidly above 0.7. Although the test results may change considerably at full scale and under actual conditons, it would seem unlikely that an increase in H/D to approximately .10 for the DC-8 from an H/D of approximately 0.8 for the 707 could account for the large UER delta. C/S PT-475 in 5.9, Vol. 2 (Reference 5), also indicates that for Boeing airplanes there is little change in the UERs for airplanes with H/Ds greater than 0.7. This line of reasoning indicates that the parameter H/D does not explain the large 707/DC-8 UER delta, therefore, the DC-8 vortex dissipators must be effective in reducing non-bird caused FOD.

Some support for this conclusion comes from data relative to the 737 fleet with and without vortex dissipators. The data sample with the dissipators is relatively small and may not be statistically sufficient. Also, it must be noted that the landing field conditions are not similar for most of the dissipator equipped airplanes. Data shown in C/S B-7465-2-76-118, REV A (Para. 3.3, Vol. 2, Reference 5), for the year 1975 shows that dissipator equipped 737 airplanes had a UER rate of 0.027/1000 engine cycles. Similar data received directly from the airlines (Para. 3.4, Vol. 2 (Reference 5)) for 1976 are shown in Table D-7. The UER rate is 0.23/1000 engine cycles for these data. Figure D-1 shows UER 737 fleet averages for the years 1975 and 1976 as 0.0033/1000 and 0.029/1000 engine

TABLE D-7. FOD DATA FOR 737 AIRPLANES USING VORTEX DISSIPATOR EQUIPMENT DURING 1976

AIRLINE	NO. FULLY EQUIPPED	NO. PARTIALLY EQUIPPED	NO. WITHOUT EQUIPMENT	GRAVEL LANDINGS	CONCRETE LANDINGS	ENGINE HOURS	FOD-EXCLUDING BIRDSTRIKES
VM	2						
SV	14				21642	39282	$1^{(1)}$
ON-HKG	1			104	1262	2555	3 BLENDS 2#2 1#1
WE	7			2270	13861	30536	$0^{(2)}$
	1				1126	1974	0
WE (1968-1976)	7 + 2 LEASE			93820		161872	1
PW	2			140	6020	7592	$1^{(3)}$
PW			10		37695	43440	$3^{(4)}$
ND	4	2		9039			0
TZ	2			748	4243	10684	$0^{(5)}$
TZ		1			2414	5450	0
PAX				1006			0
VASP	DISSIPATORS REMOVED						
AH	BIG EROSION PROBLEM (HAS MORE WIND CARRIED SAND)						

TABLE D-7. FOD DATA FOR 737 AIRPLANES USING VORTEX DISSIPATOR EQUIPMENT DURING 1976 (CONCLUDED).

(1) FOD occurred during ground run checking T/R operation.

(2) Replaced 3 first stage fan assemblies IE/P and WSB INC and/or blade damage.

(3) Blended out and airplane operated 25 additional hours.

(4) Ingested loose concrete

Ingested nose cone retaining nut

Unknown

2 cases no ER - 1 fan blades dressed, 1 fan blades replaced

54 bird strikes - in 1976, none resulted in FOD

(5) First stage fan blade removal.

cycles, respectively. Again, it appears that the vortex dissipator is effective in reducing non-bird UERs. The small number of vortex dissipator equipped airplanes does not significantly affect the fleet averages.

Since these differences are not believed to be significant factors and since they are often proprietary, they were not identified. There are differences in the materials used for various components. As an example, the RB211 and JT9D surround titanium compressor blades with steel vanes, etc. The CF6 engines use titanium for both the compressor blades and vanes in the first stages of the compressor. These types of internal design differences could result in a greater or lesser extent of damage once impacted by a foreign object, but they would not reduce the likelihood of an object entering the core. It is believed that this type difference may affect FOD costs, but not FOD occurrences. The most likely candidates to explain the low RB211 UER rates are component structural capability and basic engine configuration.

Engine characterisitcs have been used in a cursory analysis (see Appendix B) which indicates that they may very well be the key to substantial reductions in FOD and erosion. However, the preliminary nature of the analysis must be recognized. The analysis derives comparative numbers only, is indicative of directions or trends and should in no way be construed as absolute.

From the study, it appears that the RB211 fan may be much less prone to both bird and non-bird FOD primarily because of the low number of blades, which reduces the chance of an object being struck by a blade, and the low fan-blade-bending stress factor (f). The RB211 core may be much less prone to FOD. This is primarily because of the lower probability of a foreign object passing through the fan near the hub without being acted upon by the fan, and the potential for an object to be centrifuged away from the core inlet after being acted upon by the fan. The centrifuge action occurs because of the relatively large RB211 blade chord. The relatively large distance between the RB211 fan leading edge and the core inlet provides additional opportunity for a centrifuged object to pass outside of the core inlet. Blade cross sectional characteristics and other engine characteristics should be studied in detail because of the potential for large reductions in FOD resulting in UERs and decreased compressor erosion. It appears likely that FOD can be substantially reduced through engine design; however, it is not clear that such a design would result in a reduction in life cycle costs.

4. FOREIGN OBJECT INGESTION RESULTING IN EROSION

Compressor erosion has been recognized as a major contributor to engine overhaul relatively recently. For many years, overhaul occurred primarily as a result of turbine section deterioration. Higher priced fuel has encouraged compressor overhaul at the time of turbine overhaul in order to restore the SFCs associated with new engines. Statistical data relative to erosion is not available from the airline industry even today. Damage

resulting from erosion is difficult to monitor because it does not result in an identifiable event but occurs gradually over several thousand hours. The damage is generally manifest by the rounding and thinning of the compressor blades and vanes. During the winter months, many of the airports serviced by this airline use sand to provide aircraft control on the taxi areas and runways. There is verbal evidence, but no statistical data, to link the rate of erosion to the heavy sanding operations. It is known that some rather large particles are used in the sanding operations.

Information received from a major US airline indicates that the average time between overhaul (TBO) for their 747 fleet is approximately 13,000 engine hours. The TBO for the DC-10 wing mounted engines is about 7500 hours and the TBO for the number 2 engine is about 8500 hours. Since the engines for both airplanes are the same and the wing mounted engines are comparably located, these numbers indicate that the difference in TBO for the 747 and DC-10 must be due to either airport location or the number of landings. Both airplanes land at large major city airports. Therefore, the landing frequency would appear to account for the major portion of the difference. The average flight time is estimated to be 2.36 hours. Assuming that ground operation will directly affect TBO, one would expect

747 TBO to be $\frac{4.0}{2.36}$ = 1.69 longer than the DC-10 or (1.69)(7500) = 12700

hours. The correlation with reported 747 TBO is quite good considering all the other variables affecting engine TBO which may occur during take off and landing. The fact that this comparison includes 747 inboard and outboard engines and DC-10 wing- and tail-mounted engines indicates that the tail-mounted engine TBO is only 13 percent higher than the wing-mounted TBO. Whether the additional erosion on the wing-mounted engines is due to vortexing or because they are more subject to blowing debris from wind or preceding airplane, engine exhaust or nosewheel spray cannot be determined.

As with other segments of this study, there is very little data which helps determine how the erosive material gets into the engine. One bit of quantitative data, relative to 737 engine bleed tests, is included in The Boeing Company, Airplane Engine Foreign Object Damage, D6-44767, Vol. 2. This study was conducted to determine what was causing severe erosion of the turbine nozzle in the 737 air cycle machine. Bleed air contamination was measured under various operating conditions using both a "ROYCO" optical particle counting system and a Gelman Sampling Collector which uses filters. Results of the test are shown in Tables D-8 and D-9.

Small particle data in Table D-8 shows particles under 10 make up almost 90 percent of the total particulates. Over 75 percent of the particulates of all sizes are produced during taxi, takeoff roll to lift off and descent from 1000 feet to touchdown. Operation during rollout produced less than 11 percent of the particulates with or without reverse thrust. The reverser used during these tests was the original 737 reverser. This data indicates that thrust reverser operation is not a major factor contributing to engine erosion when the reverser is used as specified.

TABLE D-8. ROYCO PARTICLE COUNTER DATA (AVERAGE VALUES).

OPERATION MODE	SAMPLING TIME (SEC)	NUMBER AND PERCENT OF PARTICLES SIZE RANGE (μ) 1 ~ 5	5 ~ 10	> 10
ENGINE START	40	542 (83.78%)	62 (9.58%)	43 (6.64%)
TAXI	40	10,180 (80%)	1,302 (10.2%)	1,266 (9.8%)
TAKEOFF ROLL TO LIFTOFF	30	10,485 (72.5%)	1,978 (13.65%)	1,995 (13.85%)
LIFTOFF TO 1,000 FT	25	2,530 (76%)	419 (12.55%)	389 (11.45%)
DESCENT FROM 1,000 FT TO TOUCHDOWN	75	9,674 (73.75%)	1,790 (13.65%)	1,656 (12.6%)
TOUCHDOWN TO STOP WITH BRAKE	33	1,755 (76.65%)	285 (12.45%)	250 (10.9%)
TOUCHDOWN TO STOP WITH THRUST REVERSER	44	4,248 (77.7%)	682 (12.45%)	543 (9.85%)
AVERAGE PARTICLE DISTRIBUTION		75.5%	12.5%	12%

SAMPLING DATE - - - - SEPTEMBER 3, 1968

TABLE D-9. GELMAN SAMPLING DATA (AVERAGE VALUES).

OPERATION MODE	SAMPLING TIME (SEC)	5 - 15	15 - 25	25 - 50	50 - 100	>100
AIRPLANE TAXI	40	14,650	915	69	31	15
TAKEOFF ROLL TO 1,000 FT	55	138,500	8,100	887	332	154
LANDING WITH BRAKE	108	9,670	1,290	364	68	30
LANDING WITH THRUST REVERSER	119	14,400	1,760	164	75	27

The majority of the erosive material comes from either the sand in the concrete or blowing sand near or on the runway. Possible means of ingestion include wind, engine exhaust from preceding airplane, and vortexing. Since these tests were run at Boeing Field and Moses Lake where line ups were unlikely, it appears that wind or vortexing was the most likely ingestion mechanism for the 737 configuration tested. If nosewheel spray were the big contributor, one would expect a similar contribution during both takeoff and landing rollout which didn't occur.

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APPENDIX E

EXCERPTS FROM FAA CIRCULAR AC 33-1B

APPENDIX E

EXCERPTS FROM FAA CIRCULAR AC 33-1B
(From Reference 14)

1. INTRODUCTION

In the investigation of FOD damage to engines, the most specific reference to FOD related to the type of interest to this study was that found in the FAA document AC 33-1B. Because of what is stated, and what is not stated, the pertinent material is quoted herein. It should be noted that in all cases the particle is assumed to be airborne and ingested by the engine, although reference to how this may happen is not made.

2. BACKGROUND

Experience acquired with turbine engines has revealed that foreign object ingestion has, at times, resulted in safety hazards. Such hazards may be extreme and possibly catastrophic involving explosions, uncontrollable fires, engine disintegration, and lack of containment of broken blading. In addition, lesser but potentially severe hazards may involve airflow disruption with flameouts, lengthy or severe power losses, momentary disruptions, and possibly minor blade damage. While the magnitude of the overall hazards from foreign object ingestion is often dependent upon more than one factor, engine design appears to be the most important.

3. SCOPE

To comply with the reference regulations, engine type certification programs should include substantiation of engine ingestion properties and broken rotor blade damage containment. To insure the provision of a desired degree of engine tolerance to the disruptive effects of foreign object ingestion, substantiation should include an evaluation of the engine design and tests to demonstrate the ability to ingest typical foreign objects without causing a serious reduction in flight safety. The engine applicant is permitted to specify the use of protected inlets for his engine as an alternative to substantiation for airborne foreign objects.

4. CLASSIFICATION OF TYPICAL FOREIGN OBJECTS

For the engine substantiation program, the foreign objects considered typical are classified into two major groups.

Foreign objects in Group I are those applicable to all turbine engines and are likely to be encountered only as single occurrences affecting just one engine of any multiengine aircraft in any one flight.

a. Group I.

(1) A cleaning cloth of typical size.

(2) A mechanics hand tool of pocket size.

(3) A small size aircraft steel bolt and nut typical of aircraft inlet hardware.

(4) A piece of aircraft tire tread of length equal to the tread width of a representative size tire.

(5) Compressor and turbine blades. The most critical single blade(s), usually of the largest size, with failure assumed in or adjacent to the outermost retention member. While the majority of failures are expected to occur in the blade airfoil section, failures in or near the retention sections of the blade are also anticipated and are more difficult to contain in the engine. For integrally bladed rotors, failure of a significant portion of a blade should be assumed. While rotor blades are not normally to be categorized as foreign objects in their respective engines, failed blades are so considered for the purpose of this circular.

(6) Birds of four lbs and over (geese, buzzards, largest gulls, and ducks).

Foreign objects in Group II are those considered to be generally airborne as regards their reason for entry into engines and may be ingested by more than one engine of an aircraft on any one occasion. Since all engines of an aircraft, whether single or multiengine, may be affected by ingestions in the same flight, power recovery level is covered herein. Unless the specific installation, inlet design, or other factors preclude the possibility of the ingestion of particular foreign objects, all of the following objects are applicable:

b. Group II.

(1) Water in the form of rain and snow.

(2) Gravel of mixed sizes up to one-fourth inch, typical of airport surface material in quantities likely to be ingested in one flight.

(3) Sand of mixed sizes typical of airport surface material in quantities likely to be ingested in several flights.

(4) Ice of typical sizes and forms representative of inlet duct and lip formations, engine front frame and guide vane deposits, in quantities likely to be ingested during a flight.

(5) Hail stones of approximately .8 to .9 specific gravity and of one- and two-inch diameter.

(6) Birds in weight categories as follows:

(a) Small birds of two to four ounces (starlings)

(b) Medium birds of one to two pounds (the common gulls, small ducks, and pigeons)

5. ACCEPTABLE MEANS OF COMPLIANCE

In complying with the reference regulations relative to showing freedom from hazardous or unreliable consequences of typical foreign object ingestion, and demonstrating containment of damage from broken rotor blades, it is acceptable to conduct tests of the nature indicated in paragraph 6 to meet all of the substantiation criteria in paragraph 7. In lieu of planned official tests, pertinent related development experience, service experience, and analyses are usually acceptable means of compliance for engine substantiation. Any special engine operating precautions or techniques determined from these tests, which will aid in quickly restoring engine power or preventing further adverse effects to the engine after ingestions typical of those expected to occur in service, should be incorporated in the engine manual.

Engine substantiation may be based on consideration of only those foreign objects which are known to cause the more severe effects rather than on all typical foreign objects indicated herein.

Engines have closely spaced inlet guide vanes or air passage screens which can trap ingested debris may incur excessive gas temperature rises after ingestions, resulting in low power recovery. Whether power losses are caused by ingestion damage, air blockage from trapped birds, or other debris is immaterial, as these conditions are undesirable.

When demonstrating blade containment, the objective is to demonstrate both single blade containment and that the probability of secondary internal failures penetrating the engine cases is minimized. Unacceptable consequences have occurred from the secondary balling-up action of internal engine debris, when pieces were released with considerable energy. Some demonstration of blade containment should be accomplished with a complete engine to evaluate secondary effects of blade loss such, as severe unbalance, balling-up of blade debris, and to determine blade fragment trajectories. In fan engines, the fan assembly may be tested separately for blade containment, if it is agreed that fan blade or vane debris would not enter the compressor after a fan blade failure. Component tests with complete compressors or turbine sections are acceptable as backup tests. Substantiation should cover the effects on containment with rotor cases at the maximum temperatures reached in service.

6. SUBSTANTIATION TESTS

a. Group I, Foreign Objects

(1) Ingestion of Group I, Foreign Objects Except Rotor Blades and Large Birds, While Operating at Maximum Output

The typical objects being ingestion tested are normally introduced by dropping them into the inlet. Engine operation should be continued after ingestion to determine whether the engine is in a condition of imminent failure, particularly when some unbalance is present.

(2) Ingestion of Broken Rotor Blades

Rotor blades are to be evaluated for both ingestion effects and containment, and should be released from a rotor at maximum operating rpm, excluding transient overspeeds. The rotor blades evaluated normally include all those which, in combination with the adjacent rotor case wall section, are likely to be the most difficult to contain. If the engine continues to operate, observe a representative delay of about 15 seconds in initiating engine shutdown after the first indication of a fault from engine instruments following blade ingestion to simulate crew reaction time and determine the short term effects of operation with this unbalance. Longer post-ingestion operation should be accomplished to determine the effects of questionable internal damage which may not be readily indicated by engine instruments.

b. Group II, Foreign Objects

(1) The engine front face including the nose cone area should be tested to substantiate direct impact effects. This may be accomplished as component tests.

(2) Damage resulting from ingesting airborne foreign objects could cause blade damage or failures and tolerance to this should be evaluated with an operating engine.

(3) The provision of a windtunnel facility to provide a moving airstream into the test engine is desirable, but is not essential where the injection of the foreign objects into the operating engine to simulate the effects of aircraft speed is adequate. Whenever results considered particularly critical to safety result from ingestion tests, however, it is desirable to conduct either a windtunnel test, a flight test, or a particularly accurate simulation of flight effects on the severity of ingestion effects. As an example, the minimum propeller blade pitch settings used with the turbopropeller engines in flight may require special test settings under static test stand conditions to simulate flight operation characteristics.

(4) Duration of the engine running following ingestion of any Group II objects should be at least five minutes to determine whether the engine is in a condition of imminent failure but, in case of doubt as to actual engine condition or evident engine damage, longer post-ingestion tests runs should be conducted.

7. SUBSTANTIATION CRITERIA

a. Group I Objects

The engine is acceptable if ingestion tests demonstrate freedom from engine explosion, disintegration, or uncontrollable fire. It is acceptable that the engine may require shutdown, but this should be indicated by excessive vibration or other direct operating evidence in a timely manner which would permit a safe shutdown.

b. Group II Objects

The engine is acceptable if tests demonstrate freedom from the foregoing hazards and the ability to minimize overall hazards and potentially serious conditions, with the quantities and conditions indicated, by its continued safe operation after the ingestion tests. There should be no indication of need for immediate shutdown or imminent failure during the ingestion tests, and prompt engine recovery should be obtained. There should be no flameouts or significant sustained power loss from ice, hail, or water ingestion or hazardous effects from case contraction from the water ingestion tests. Power recovery to stabilized operation following other Group II ingestions may be at reduced levels and the desired minimum level is 75 percent.

APPENDIX F

PARAGRAPHS FROM MIL-E-5007D
WHICH RELATE TO FOD

APPENDIX F

PARAGRAPHS FROM MIL-E-5007D WHICH RELATE TO FOD
(From Reference 6)

1. FOREIGN OBJECT DAMAGE TEST

The test engine shall be subjected to a foreign object damage test to demonstrate compliance with Para. 4. Simulated foreign object damage shall be applied to three first stage blades at one or more sections of the leading edge at a location where high steady-state and vibratory stresses occur at maximum engine speed. The damage applied shall produce at least a stress concentration factor (K_t) of 3. Following the foreign object damaged application, the engine, with damage blades installed, shall be subjected to one 6 hour cycle of running in accordance with the cycle of operation in 4.6.1.3. No calibration or recalibration shall be required for this test. At the completion of the running, there shall be no evidence of blade failure or cracking as the result of the foreign object damage.

Subject to approval of the using service, the foreign object damage test may be conducted by bench testing on individual blades or rig testing on full scale fan or compressor components in lieu of complete engine testing.

If the test is to be conducted on a component basis, details of the test shall be presented in the pretest data. However, conditions, duration, and severity of testing shall be equivalent to the complete engine test described above.

2. ICE INGESTION TEST

The test engine shall be subjected to an ice ingestion test to demonstrate compliance with the requirements of Para. 5. The type of ice and the conditions for ingestion shall be as follows:

a. One, two (2) inch diameter hailstone and two, one (1) inch diameter hailtones of 0.80 to 0.90 specific gravity for each 400 square inches, or fraction thereof, of inlet area at the engine face at typical takeoff (maximum), cruise, and descent conditions.

b. Sheet ice of 0.80 to 0.90 specific gravity in typical sizes, forms and thicknesses, as approved by the using service representative of inlet duct and lip formations in quantities likely to be ingested during takeoff and cruise conditions.

The contractor shall specify in the pretest data the procedures to be used for introduction of ice at the engine inlet, the engine power settings, and speed at which the ice or hailstones are to be ingested. The

time for engine power recovery shall be recorded. During the tests, high speed photographic coverage of the inlet is required. The test will be considered to be satisfactorily completed when, in the judgment of the using service, the performance criteria of Para. 5 has been met and there is no evidence of major structural damage which could cause the engine to fail.

3. SAND INGESTION TEST

The test engine shall be subjected to a run of ten hours' duration at maximum continuous thrust, with stand contaminant in accordance with Para. 6 introduced into the engine inlet. During each hour of operation, at least one deceleration to idle and acceleration to maximum continuous thrust shall be made with throttle movements within 0.5 seconds. During the first hour, ten one-minute operations of the anti-icing system, if provided, shall be performed. During the entire test, maximum customer bleed air shall be extracted from the engine. This air shall be continually filtered, the total deposits measured, and results reported. Following the 10-hour run and post test performance check, the engine shall be disassembled as necessary to inspect for the extent of sand erosion and the degree to which sand may have entered critical areas in the engine's internal air cooling system. The test will be considered to be satisfactorily completed when, in the judgment of the using service, the performance criteria of Para. 6 have been met and teardown inspection reveals no failure or evidence of impending failure.

4. FOREIGN OBJECT DAMAGE (FOD)

The engine shall operate for two inspection periods or the number of hours specified in the engine specification after ingestion of foreign objects, which produce damage with a minimum stress concentration factor (K_t) of 3 to fan, compressor blades, and stators.

5. ICE INGESTION

The engine shall be capable of ingesting hail, and any ice which accretes on engine inlet parts without flameout, lengthly power recovery, sustained power loss exceeding 10 percent of the thrust at the operating condition, or catastrophic or critical engine failure. The time for power recovery shall be specified in the engine specification. When required by the using service, the engine shall also be capable of ingesting shed ice and shall be subjected to the sheet ice ingestion test of Para. 3.b.

6. SAND INGESTION

The engine, including all components, shall operate satisfactorily throughout its operating range at ground environmental conditions with air containing sand and dust in concentrations up to 3.3 x 10^{-6} pounds of sand per cubic foot of air. The engine and its components shall be capable of operating at maximum continuous thrust with the specified concentration of

sand and dust for a total period of 10 hours with not greater than 5 percent loss in thrust, 5 percent gain in specific fuel consumption, and no impairment of capability to execute thrust transients. The specified sand contaminant shall consist of crushed quartz with the total particle size distribution as follows:

PARTICLE SIZE, MICRONS	QUANTITY, PERCENT BY WEIGHT FINER THAN SIZE INDICATED
1,000	100
900	98 - 99
600	93 - 97
400	82 - 86
200	46 - 50
125	18 - 22
75	3 - 7

APPENDIX G

DISCUSSION OF SELECTED BOEING TEST DATA

APPENDIX G

DISCUSSION OF SELECTED BOEING TEST DATA

1. INTRODUCTION

Because of the small amount of test data, several of the most pertinent accumulations of test data were reviewed (Reference 5, Volume 2, and References 18 and 19) for insights pertinent to the FOD analysis. This appendix briefly presents the highlights from these testing reports. The purpose is to present in a more complete form such information insights and data as exist. Further, some experience from use of propeller driven aircraft were included because of interest in the C-130.

2. TEST INSTRUMENTATION

Two Boeing test data collection methods were used: observation and high speed photography. In addition, a series of bins were constructed to be towed behind nose landing gear in a test region. These were used to measure the amount of debris in various positions. Due to the number of bins and the amount of objects normally thrown up by the wheel, a great deal of effort was necessary to obtain substantial data.

3. BOEING INITIAL EXPERIENCE

a. Introduction

When Boeing started to address the problem, flights with Alaska Airlines and with Wien Air Alaska were made to study gravel runway operation using F-27's. The Fairchild F-27 is well suited to such a study since the main gear is visible from the passenger cabin, providing ease in obtaining visual and photographic observations of gravel activity on landing and takeoff.

b. Current Gravel Runway Damage Experience

The following two airplanes evidence typical examples of gravel runway damage.

(1) Fairchild F-27

The effect of operation on gravel runways was evident on the exterior of the F-27. The effect of a propeller blade striking a stone was also a cause of some damage. The fuselage scars in the propeller plane were not caused by gravel but by propeller icing. Figure G-1 is a diagram of the F-27 showing the general limit of rock activity. Areas with high moderate incidences of rock strikes are shown; however, rock strikes actually extended farther aft than the diagram depicts. In these areas no physical evidence of rock strikes could be seen due to the near tangential

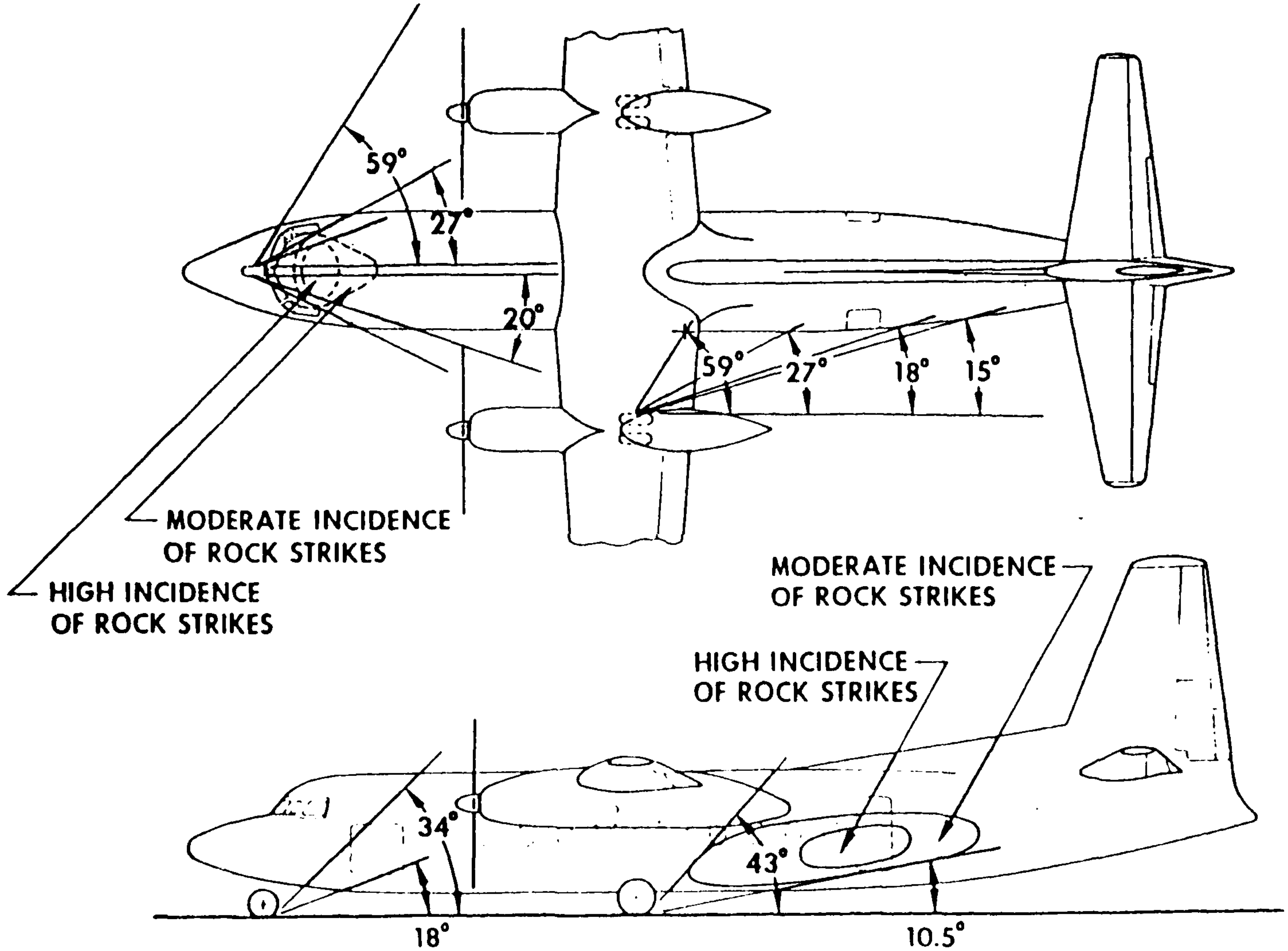

Figure G-1. Diagram of F-27 Showing Rock Stricks.

contact with the airplane. The rock velocity component normal to the skin was insufficient to cause damage to skin or paint.

(2) Lockheed L-749

The L-749 landing gear is long, placing the fuselage about six feet off the ground. No evidence of gravel damage on the fuselage was found, indicating the existence of an upper limit to gravel trajectories. The flaps directly aft of the main gear showed the effect of gravel thrown up by the main gear tires and disfigurement was evident on the .032 flap skin, although perforation did not occur.

c. Investigation of F-27 Operations

The study of the nature of gravel runway airplane problems was begun by observation of F-27 operations. The main gear was visible from the passenger cabin and observations could be easily made on regularly scheduled passenger flights. These studies were undertaken to establish the nature of the problem, source of physical damage to the airplane, and the possible hazard to safety with a jet engine due to gravel ingestion.

Through a cabin window both visual and photographic observations were made on gravel runway landings and takeoffs. Movies were made at 64 frames per second, which proved to be too slow to stop flying gravel. A further limitation was the single view point. Consequently, externally mounted cameras were used on special test flights to improve observation of gravel activity.

The special test flights were performed at Fort Yukon, Alaska. The runway was typical of gravel runways found in Alaska, with perhaps more loose gravel than some. For the tests, two externally mounted cameras were used. One camera was mounted in front of the left main gear looking aft and another camera was mounted looking forward at the nose gear. These cameras operated at 200 frames per second and showed the cause and direction of most rock activity.

One particularly perplexing question arose with the discovery of gravel inside the F-27 main gear wheel well. This wheel well is forward of the wheels and it appeared impossible for gravel from either the nose or main gear to reach it. On all landings and takeoffs observed there were no indications that gravel was ever thrown this high or in this direction. On a landing at Point Barrow where the runway was intermittently covered with thawing snow, it was observed that between the wheels the slush was carried upward while at the outside the tires merely sprayed the slush to the side with a lesser vertical component. The conclusion that there was an interaction between the dual wheels was confirmed later in the Boeing field tests.

The most significant finding was that very little rock throwing occurred on either landing or takeoff unless a wheel rolled through a deep

layer of gravel. This incidence of flying gravel was actually too low to enable a conclusive study of the problem.

4. BOEING FIELD VEHICLE TESTS

The low incidence of flying gravel actually found in service made it impossible to accurately establish the full nature of the gravel runway problem. This led to the decision to build a ground test rig where a loaded wheel could be rolled through a deep bed of gravel designed to be, throughout its length, equal or worse than the local spots of deep gravel actually found on gravel runways. The test bed would then cause a continuous spray of gravel which could be more easily analyzed.

5. DATA COLLECTION FOR 737

a. Summary

A full scale model of a 737 nose gear was driven over a gravel surface constructed to simulate gravel runway conditions. Motion picture coverage of the movement of rocks disturbed by the wheels and quantitative data on rock distribution, as determined by a count of rocks caught in a net surrounding the gear, was obtained.

The basic rock motion may be described as follows. A wheel rolling over a gravel surface forces the rocks in its direct path downward. The downward motion of rocks in the center area of the wheel path causes rocks at the edge of, and adjacent to, the wheel path to be expelled outward and upward. To an observer on the gear, a large percentage of the rocks expelled are contained in a side wave which originates at the forward edge of the foot print, fans out behind the wheel at a maximum angle of 15 to 20 degrees, and reaches a height of 18 to 24 inches. The trajectories of rocks within this general wave envelope are such that they will not cause structural damage. However, a small percentage of rocks are expelled with wider and higher trajectories that may easily intercept the engine inlet. Test runs with the Phase II net at the -100 and -200 engine hi-lite positions intercepted a sufficient number of rocks to indicate a potential for engine damage.

Comparison of bare gear and deflector installed test results indicate both the rubber disc and raked brush concept suppress a large percentage of the side wave. The flat raked brush and the cupped rake brush have approximately the same effectiveness and are superior to either of the flat rubber discs. However, to establish the actual effectiveness of any deflector, it will be necessary to establish a relationship between test conditions and actual operating conditions. The primary factors that influence the amount and intensity of rock action are: looseness of the gravel surface, wheel loading, wheel alignment with direction of travel, vehicle speed and sink rate at touchdown. At the present time, the relationship between test conditions and operating conditions with respect to

these factors is not clearly evident and the sufficiency of the deflector control can only be estimated.

b. Discussion of Test Runs

The complete test program was divided into four series of tests with each series unique as to its gear and net configuration. The first series consists of the Phase I tests, runs 1 through 41, which were made with the single wheel gear, Goodyear tire, and Phase I net. This period provided opportunity for the checkout of the test vehicle and provided information basic to the following description of rock action.

As the wheel rolls over the surface, rocks in the center portion of the wheel path are displaced downward. This movement tends to expel rocks at the edge of and adjacent to the wheel path outward and upward. To an observer on the gear, the rock motion appears to be in the form of a side wave originating near the forward edge of the footprint and finning out behind the gear. The angle of the wave, as measured with respect to the wheel plane, varies to some extent with speed and reaches a maximum of 15 to 20 degrees at vehicle speeds of 45 to 50 mph. Above the speed the angle tends to decrease. As observed with respect to the ground, the expelled rock tend to move in a plane at 90 degrees to the direction of vehicle travel. The observed maximum side wave angle implies that the rocks reach a maximum horizontal veloticy of 15 to 20 mph. No evidence of rocks being expelled forward of the wheel was observed. As a result of these observations, a test speed of 40 to 45 mph was selected for the deflector evaluation tests of Phase IA. This speed produced a near maximum rock action and did not require the additional thrust of the jet engine.

The first brush deflectors, 1.10 and 1.20 were tested. Because of their radial construction, the bristles of these brushes were placed under a column loading as the wheel rotated. The bristles became permanently deformed and tangled after a few revolutions and for this reason the brushes were judged unsuitable for airplane application. Tests were discontinued and no attempt was made to evaluate their control effectiveness.

Deflector 1.30 was made up and tested to determine if a raked bristle construction, which would subject the bristle to a side rather than a column loading, would suffer less deformation. After nine test runs (32 through 40) the bristle remained in good condition except for some fraying at the bristle ends. Photographic records of these runs show good suppression of the side wave with this deflector.

A study of motion picture data of runs with the Phase I net revealed that a heavy concentration of rock was striking the lower net structure and many rocks from this region were being deflected into net positions by indirect routes. The planned method of deflector evaluation was to compare the rock catch at critical positions made with and without a deflector. The basic assumption of this method was that rocks retained in

a particular net position reached that position by direct route from the wheel. The large number of deflected rocks made this assumption invalid and for this reason no attempt has been made to evaluate the effectiveness of deflectors tested during Phase I tests.

Tests with deflectors 2.10 and 2.20 indicated that this type of deflector would need a staff center area to prevent wobble and then taper to become a flexible member in the region of ground contact. These deflectors also had a tendency to throw rock because of their cup shape. On the only run with deflector 3.10, the rubber flap rolled up between the supporting aluminum sheet and tire. The run was inconclusive as to rock deflection. During the approach of the second run the test article was torn from the gear when it struck a rise in the pavement. This emphasized that a major disadvantage of the fixed flap concept is the limited structure for attachment.

The second series consisted of the Phase II runs made with the engine position net and dual wheel gear. The significant fact of this series is that sufficient rocks were intercepted to have caused engine damage. A total of 20 rocks were caught during the first 20 runs of the series. The largest number to be intercepted on a single run (No. 47) was eight. During this run the gear was lowered to simulate landing conditions and the photographic record of the run shows most of the rock caught were thrown from the wheel at touchdown. Although the test speed was too slow for true landing simulation, the test does indicate the landing operation to be the worst condition. During the last two runs of this series, the 2.40 deflector was installed and no rocks were intercepted.

The Goodrich dimple tread tire was used for this series of tests. This tire has a cross section profile with only a slight curvature in the tread region, whereas the Goodyear tire is nearly round in cross section. The objective of testing with this tire was to determine the effect, if any, of the cross section profile. No significant difference could be observed. However, the loose gravel condition of the test section may have hidden small reductions in the amount of gravel thrown.

The third series of tests was made with the Phase IA net. The objective of this series was to compare deflector effectiveness for rock count data. To obtain an acceptable average of rocks per run at critical locations, each deflector configuration was subjected to a minimum of 30 test runs. The dual gear was used to induce wheel interaction effects into the test results. The Phase I net was modified to remove baskets in those non-critical areas having a high concentration of rock impingement and to make engine line baskets conform to the dual gear geometry. The removal of the lower center baskets reduced the number of rocks deflected by the net structure and increased the accuracy of the rock count data.

During the Phase IA series, which consists of runs 61 through 113B, tests were made with the bare gear and deflectors 0.01, 1.40, 1.50, 2.30, and 2.40. A summary of the data indicates a substantial reduction in

the number of rocks retained in the left hand engine line positions for each deflector test series. Deflector evaluation is complicated by the fact that a similar but smaller reduction is noted for the right hand opposite positions unprotected by the deflector installations. This indicates that the number of rocks thrown is strongly influenced by surface condition and vehicle path through the test section. In particular, the bare gear series was influenced by the addition of gravel to the test section between runs 66B and 67. This addition was necessary to fill soft spots which developed after rain softened the test section.

It is the opinion of the writer that the Phase IA net, since it is relatively close to the gear and does not consider the entire rock trajectory, is mainly a comparative device and does not give a complete picture of deflector effectiveness. To determine if a deflector does or does not give adequate protection, it will be necessary to test it with the net-simulating engine position or otherwise determine if rocks are eliminated from the inlet region.

The fourth series of tests were water spray to obtain preliminary information on the possibility of water ingestion during wet runway operations. The tests were conducted through the 80 foot long concrete trough on the west taxiway. Test speeds ranged from 30 to 70 mph and water depth averaged approximately 0.5 inches. From ground observation and study of test films it was concluded that the main body of the spray pattern would fall inboard and aft of the engine inlet. No measurable amount of water was collected in the collection tubes mounted on the engine position net. The net, however, did show some dampness after runs indicating small amounts of water might enter the inlet. The worst spray conditions were observed in the 35 mph range and therefore the speed range of these tests should be valid for all airplane operating conditions.

6. SUMMARY OF INSIGHTS GRAVEL EXCITATION PHENOMENA

Detailed examination of the high speed film of the Alaska tests and the Boeing Field tests determined the following about the phenomena of gravel excitation:

a. There is no "bow wave" effect. At touchdown no rocks are thrown ahead of the tire.

b. A trampoline effect exists directly behind the tire wherein the rebound of the soil tosses the surface gravel into the air. The height of these stones varies with weight and speed of the aircraft, but are normally only 6 to 10 inches in height. These stones have only a vertical motion component.

c. Another effect which can only be understood by deduction, since no photographic evidence could be found. When the F-2, nosewheel touches down, rocks could be heard striking the fuselage directly behind the nose gear. Evidence of this could also be seen on the fuselage skin as

scratches in the paint. One possible explanation is that the stones were raised by the trampoline effect and then received an aerodynamic boost from the movement of air adjacent to the rotating tire.

It is conceivable that small stones could adhere to the grooves in a tire and be thrown tangentially, but this was never detected in all the movies examined. If such an effect occurs, these stones must be thrown free at a very low angle immediately after the tire breaks contact with the surface of the runway, for at this point the stone would have exerted upon it the full centrifugal force.

d. When a tire rolls through a ridge of gravel 2 to 4 inches deep, a sideward spraying of rocks occurs, which is very similar to a water spray. This effect varies with aircraft speed and depth of loose gravel. It is possible for these rocks to be thrown approximately 4 feet high and 10 feet to one side.

e. The side spray effect also occurs between dual wheels, but in this case the sprayed rocks strike the opposite tire or wheel at a point where it is moving with an upward component. This causes the stones to ricochet upward and sometimes forward.

This dual wheel interaction is considered to be the only effect which warrants the use of stone suppression devices for 727 gravel operation. An effective stone suppression device would substantially reduce flap damage caused by the dual wheel interaction.

f. The tiddly-wink effect is conceivable, but could not be observed in any of the high speed movies that were made. This is apparently due to two causes:

(1) A gravel runway surface is too soft to react to the squeeze of the tire on a stone to create a side component of force, or

(2) The stones responding to this effect, if it does occur, are confused with those that are sprayed to the side.

g. Stones occasionally bounce along with the airplane at approximately vehicle speed and direction. These are apparently rebounding from airplane structure or landing gear after having been excited by the wheel as described in (5) above. The occurrence of this action is found to be infrequent, and due to their direction and relative velocity, these stones do not constitute a problem.

h. During F-27 tests, speed of touchdown was varied from 93 to 112 knots. No difference in the effect on the gravel activity was detected over this speed range. Similarly, the touchdown impact was varied from a very smooth "greased in" landing to a hard touchdown with several bounces. No difference in gravel activity was detected for either type of landing. During the hard landings, the wheels were rotating for the second and third

touchdown with noticeable gravel only being raised on the first touchdown. This would indicate that the initial wheel spin-up causes substantially more gravel action than does the rolling tire. The degree of rock activity was also determined to be a function of gravel depth. Since patches of deep gravel are usually found near the ends of the runway, the touchdown is far more severe than any other time, even the higher speeds used for take-off.

Testing with the gravel test rig was performed at three speeds: 25, 45, and 75 mph. The most severe gravel action was observed at 45 mph and above. At slower speeds, the vehicle did not transfer as much energy to the gravel. At speeds above 45 mph, the vehicle tended to outrun the gravel; however, the height of gravel thrown remained about the same.

It can be concluded that at the higher speeds involved in 727 operation, approximately 130 knots takeoff speed and 115 knots landing speed, will not cause the gravel action to be different or more severe than that observed in the test program. As a pictorial summary, Figures G-2 and G-3 show the results of investigations of the 727 and 737 aircrafts respecitvely.

7. GRAVEL RUNWAY COMPARISON DATA

Due to the focus on gravel runways, the following is presented to give some detail on the runways encountered in operation. Alaska Airlines operate in and out two gravel runways for which 727 gravel runway certification is required. These are Kotzebue and Unalakleet, Alaska. These runways will not be representative of their worst condition, due to weather conditions when certification testing is to be conducted. Therefore, an equivalent alternate gravel runway is required. The runway selected is the gravel runway on Annette Island, Alaska.

By field identification method, these three runways compare as follows:

a. Kotzebue - Runway 8/26

Well-graded, gravelly sands with little or no fines. Classification SW per the Unified Soil Classification, Corps of Engineers, Bureau of Reclamation, and of the following composition:

Over 99% passing 2-1/2 inch square sieve
55% passing U.S. No. 4 sieve
Less than 5% passing U.S. No. 200 sieve

California Bearing Ratio = 35

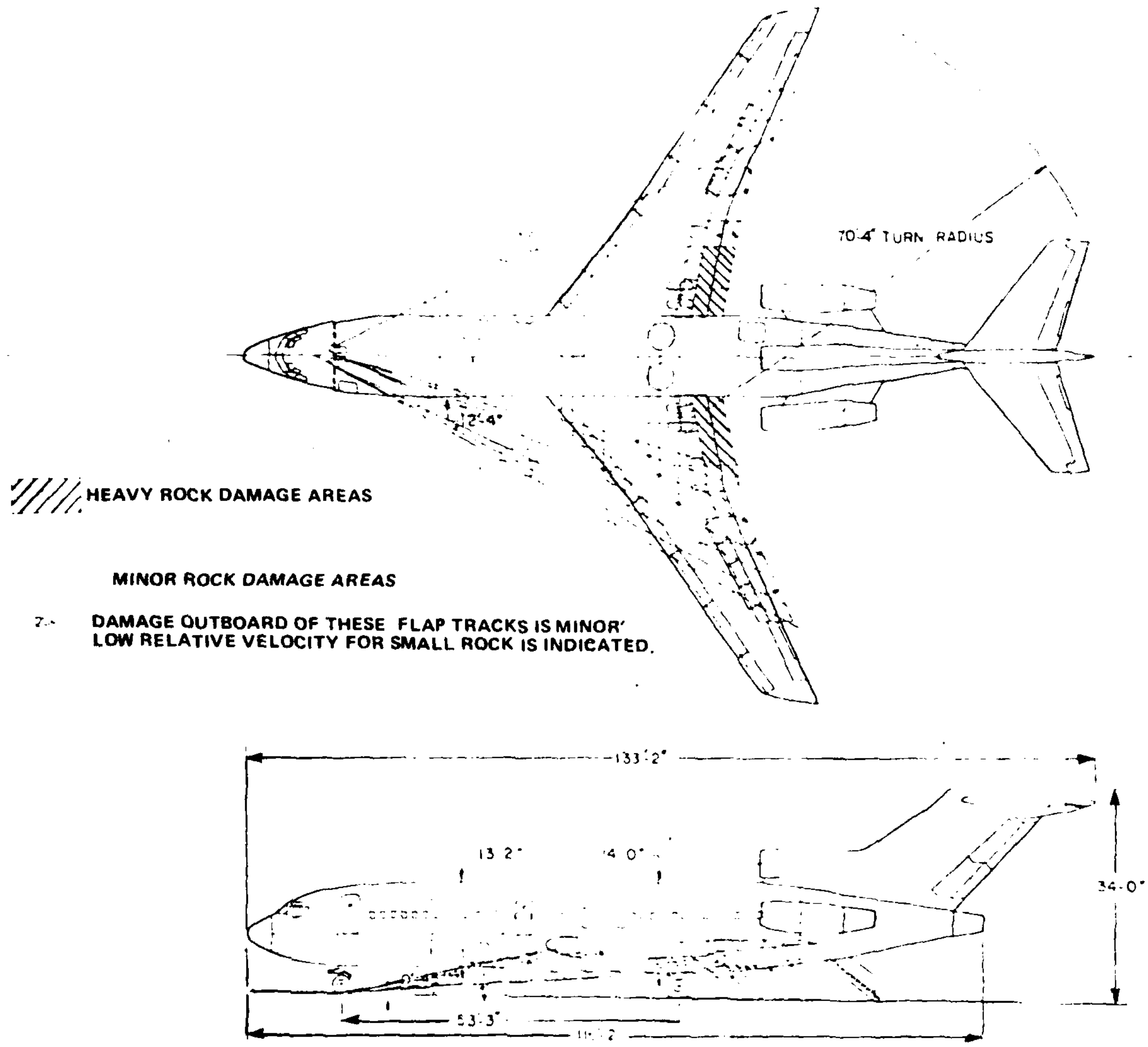

Figure G-2. Rock Impingement on 727 (Gravel Runway Operation).

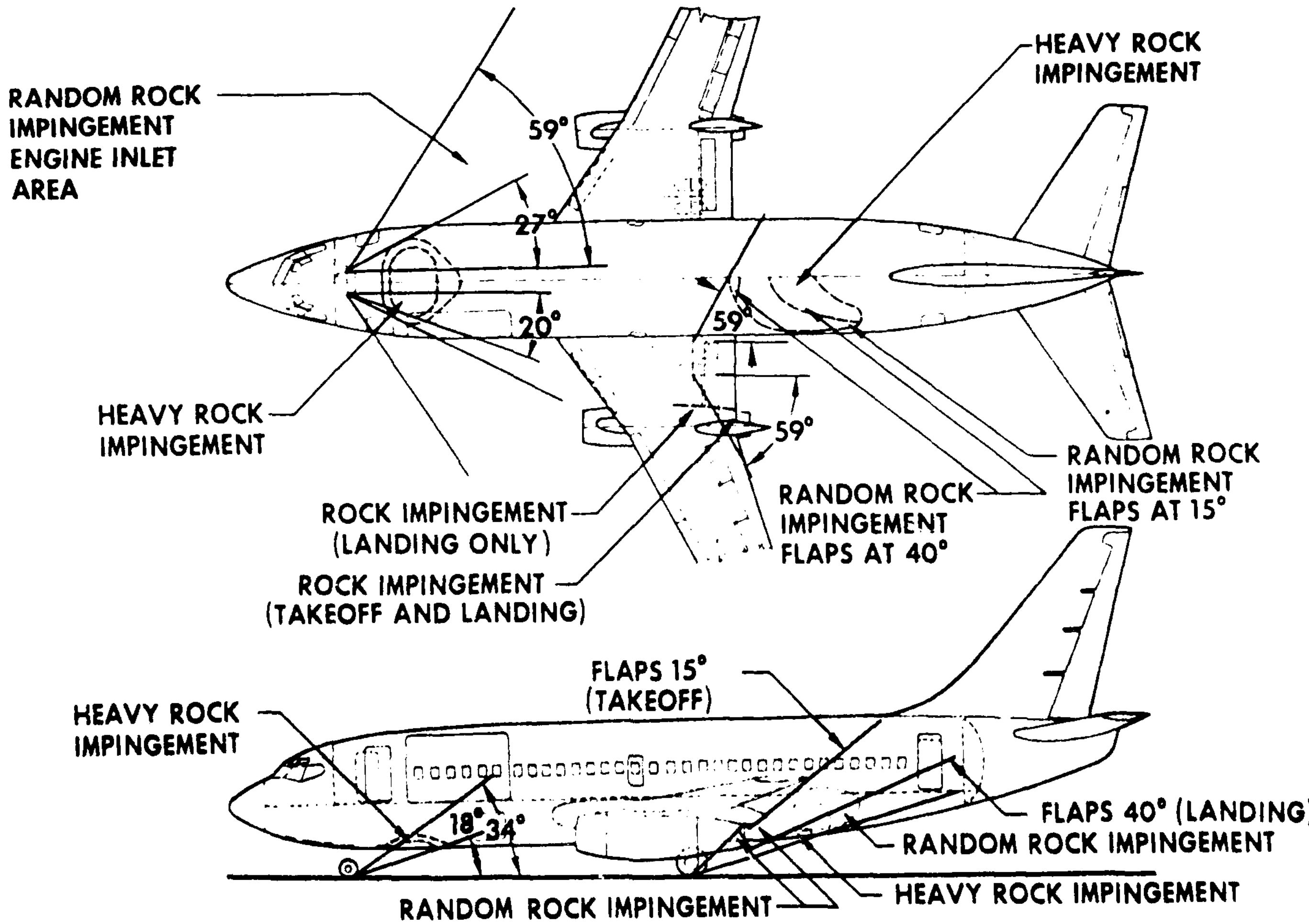

Figure G-3. Rock Impingement on 737 (Gravel Runway Operation).

b. Unalakleet

Silty sand-gravelly. Classification SM per Unified Soil Classification and of the following composition:

100% passing 2-1/2 inch square sieve
Over 55% passing U.S. No. 4 sieve
Over 12% passing U.S. No. 200 sieve

California Bearing Ratio = 40

c. Annette Island - Runway 2/20

Gravel-sand-clay mixture. Classification GC per Unified Soil Classification, and of the following composition:

Over 99% passing 2-1/2 inch square sieve
45% passing U.S. No. 4 sieve
Over 12% passing U.S. No. 200 sieve

California Bearing Ratio = 41

The following Figure G-4 shows the data used by Boeing to estimate applicability of these runways.

8. USE OF DATA TO COMPUTE ESTIMATES OF EFFECTIVENESS

The basic data that was collected could not be compared directly, due to the shift in level or rock count that was apparent in the baskets of the right hand or inboard side of the net. Since, during the entire test phase, no changes were made to the inboard side of the test gear or net, and all the deflectors were mounted on the outboard side of the test gear or between the 2 wheels, it was assumed that the difference in the level of lower inboard rock count was caused by a change in surface conditions. From the basic data an attempt has been made to reduce the series to a common denominator to eliminate these differences in the test bed surface conditions. This has been done by taking the results obtained in the lower row of baskets on the inboard side. Using the bare gear or no deflector series as a basis, the factor is calculated such that the maximum positive and negative deviations from the bare wheel series are equal. The factors obtained are as follows:

727 Center Deflector Series	2.35
L0737 NG31 - 1 Series	2.00
L0737 NG31 - 2 Series	1.95
L0737 NG23 - 5 Series	2.10
L0737 NG23 - 9 Series	1.42

Figure G-5 and G-6 shows some basic, uncorrected rock counts. Figure G-7 shows the gravel spray pattern, obtained during this testing,

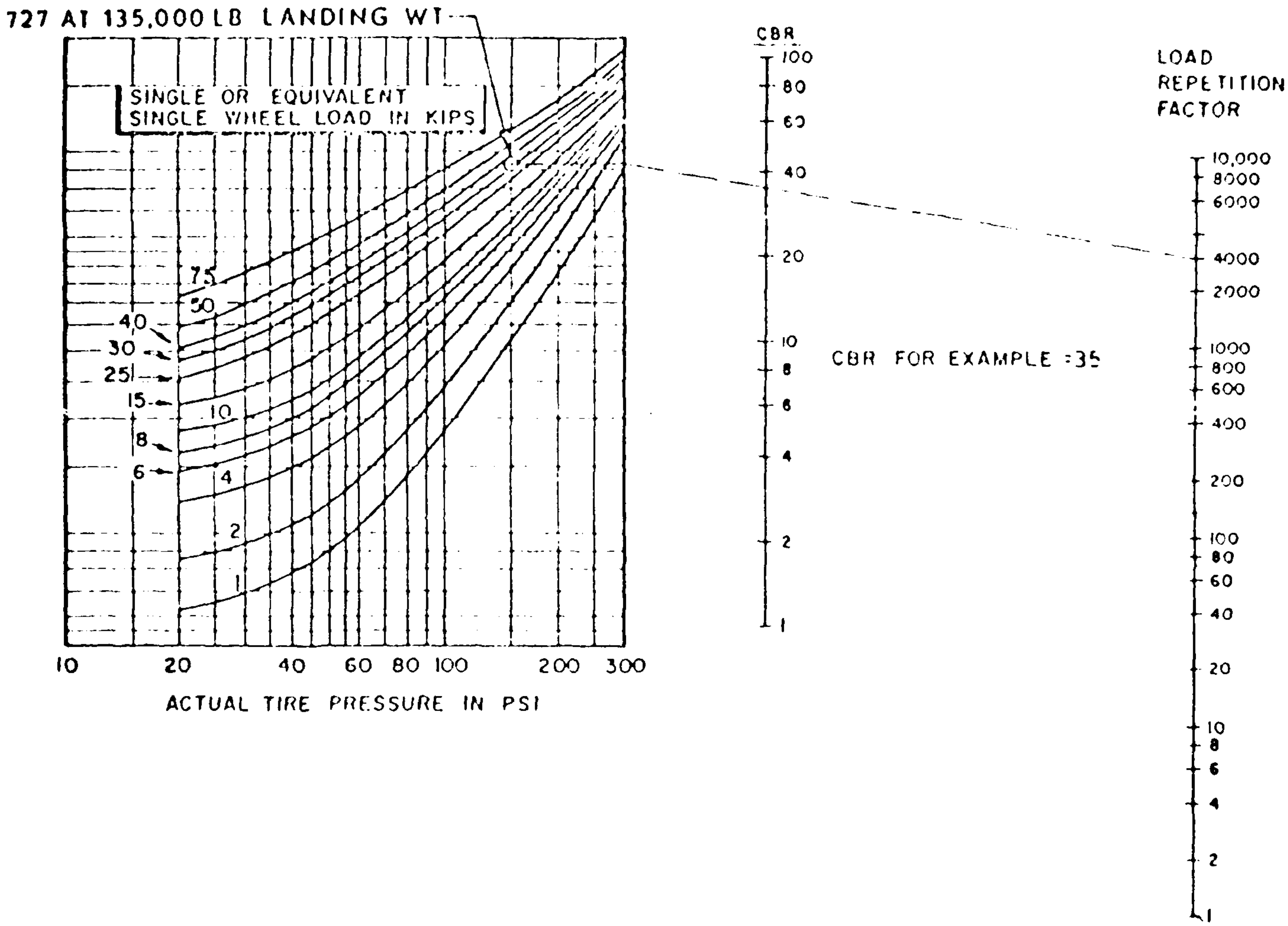

Figure G-4. CBR Required for Operation of Aircraft on Unsurfaced Soils.

MODIFIED PHASE I NET ~ DUAL WHEEL

← RIGHT HAND SIDE | LEFT HAND SIDE →

.12	.31	.23	.12	.39	.35	.56	.33	.23	.07	.02
.12	.23	.60	.89	1.31	1.01	1.10	.80	.45	.11	.11
.52	1.21	1.76	1.35	5.32	5.22	8.37	4.85	2.60	.75	.32
	13.80							19.55		
BASKET AREA ~ FT² 3.54	1.18	1.12	1.12	1.72	1.72	1.12	1.12	1.18	1.77	1.77

VIEW LOOKING AFT

CONFIGURATION NO DEFLECTOR

RIG SPEED 45 M.P.H.

RUN NO'S 61 THROUGH 70, 71A THROUGH 71G (30 runs)

Figure G-5. 737 Gravel Runway Test Rock Count Per Run Per Ft².

MODIFIED PHASE I NET ~ DUAL WHEEL

RIGHT HAND SIDE | LEFT HAND SIDE

	.01	03	.06	.14	.07	.22	.17	.14	.11	.02	0
	.04	.11	.31	.31	.80	.78	.67	.34	.11	04	0
	.11	.69	1.17	2.74	3.93	4.69	3.49	.45	.08	.04	0
		6.49							.53		
BASKET AREA ~ FT²	3.54	1.18	1.18	1.12	1.72	1.72	1.12	1.12	1.18	1.77	1.77

VIEW LOOKING AFT

CONFIGURATION RAKED AND DISHED BRISTLE BRUSH

RIG SPEED 45 M.P.H.

RUN NO.'S 101 THROUGH 113 B (32 runs)

Figure G-6. 737 Gravel Runway Test Rock Count Per Run Per Ft².

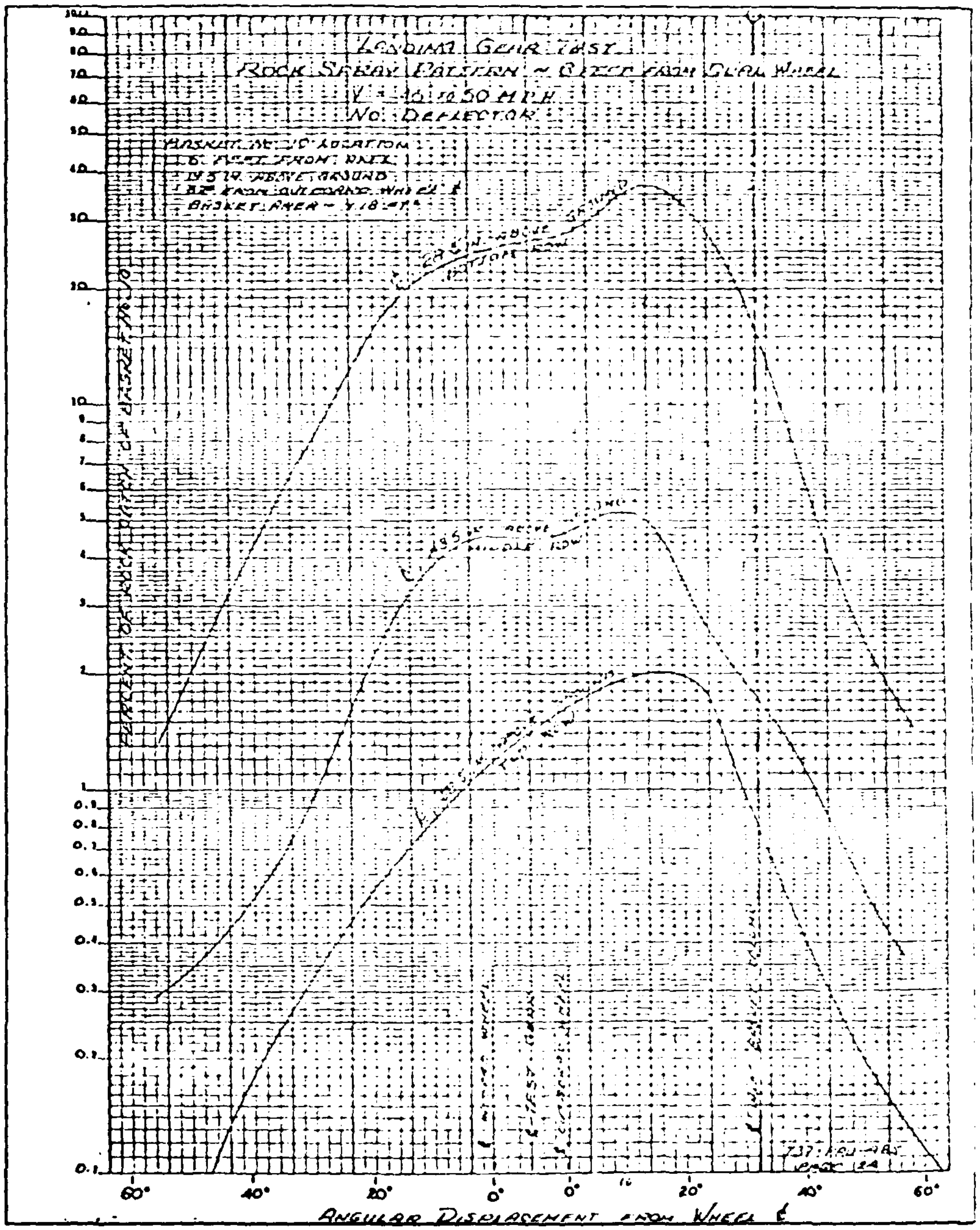

Figure G-7. Landing Gear Test Rock Spray Pattern.

for a bare dual wheel configuration. The data is presented as a percentage of the gravel caught in the lower basket of the outboard inlet column. From this figure it can be seen that the maximum gravel action occured between 10 degrees and 15 degrees outboard of the outboard wheel. This is attributed to the fact that during the testing the rig was turned into and then out of the test bed which caused some tire scrubbing.

Figure G-8 shows the gravel spray pattern from a dual wheel with the effect of the brush type deflector (L0737NG23 -5 and -9) and the 727 center deflector mounted. From these figures a deflector effectiveness can be calculated.

	Percent of Basket No. 10 Rock Catch At centerline of Inlet Basket Column	
	Bare Wheel (Ref. Fig. G-7)	L0737NG23-9 (Ref. Fig. G-8)
Basket No. 10	100	3.85[1)]
Basket No. 9	15.5	0.52
Basket No. 8	1.70	0.81
Basket No. 7	0.79	0.26
TOTAL	117.99	5.44

1) From Figures G-5 and G-6 $\quad 3.85 = \dfrac{\overset{53}{1.42}}{19.55} \times 100.$

$$\text{Deflector Effectiveness} = \frac{117.99 - 5.44}{117.99} \quad 100 = 15.5\%$$

This would result in reducing the ingested gravel per airplane per flight to 0.317 rocks in 1.12 pebbles. Figure G-9 shows the size of rocks and pebbles.

9. BOEING REVIEW OF AERODYNAMIC INGESTION IN 1972

a. Background

This discussion considers the engine inlet ingestion characteristics on a number of airplanes. For the purposes of this evaluation only aerodynamic ingestion, i.e., "vacuum cleaner effect" is considered.

Aerodynamic ingestion of foreign objects by engines occurs at the beginning of the takeoff roll and during taxi and static operations. The mechanism by which these foreign objects are ingested is as follows: A vortex is formed in front of the engine inlet and disturbs objects lying on the ground. These objects tend to be thrown out horizontally by the vortex action. On hard surfaces, i.e., paved runways, these objects are not

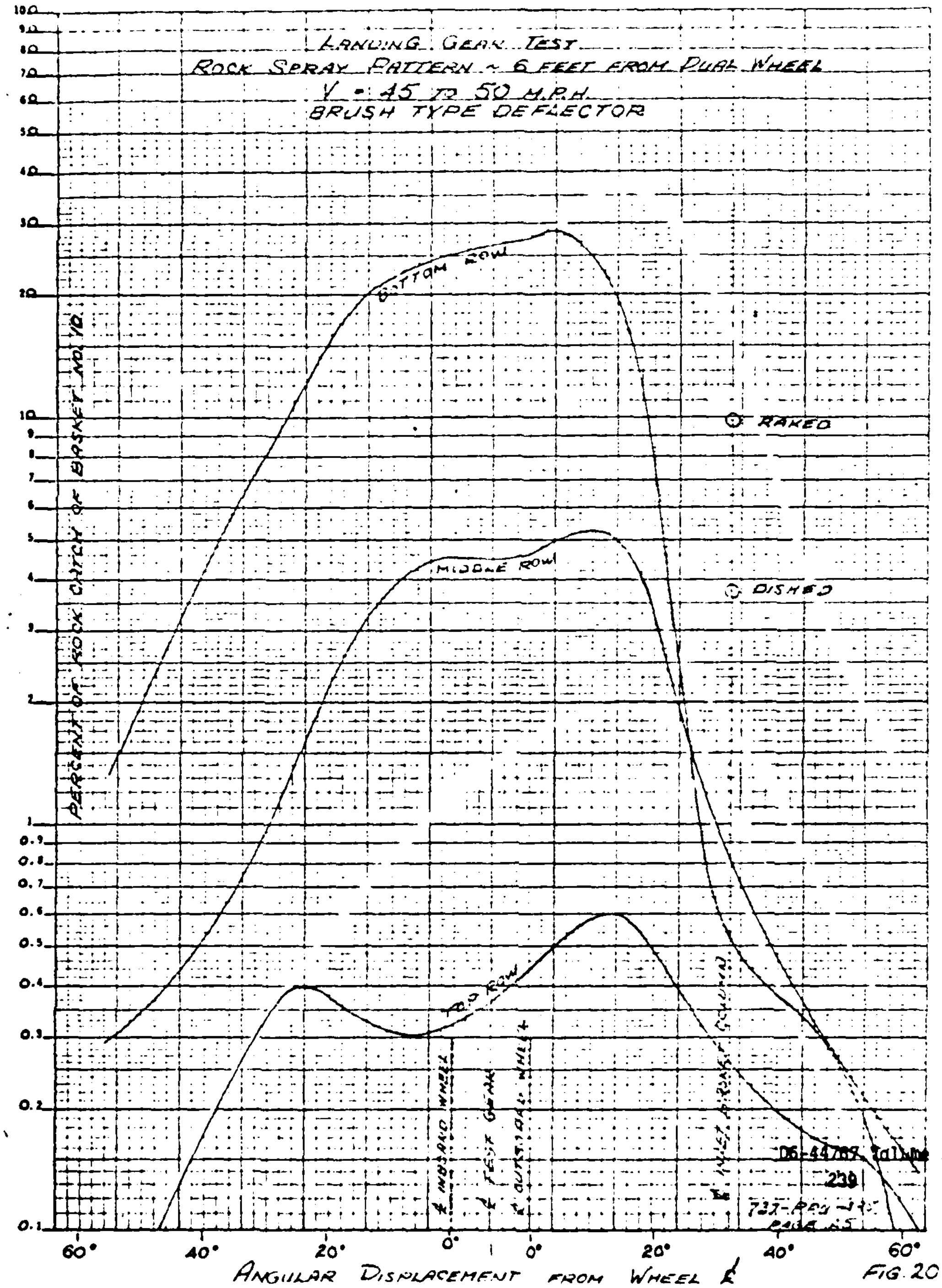

Figure G-8. Landing Gear Test Rock Spray Pattern.

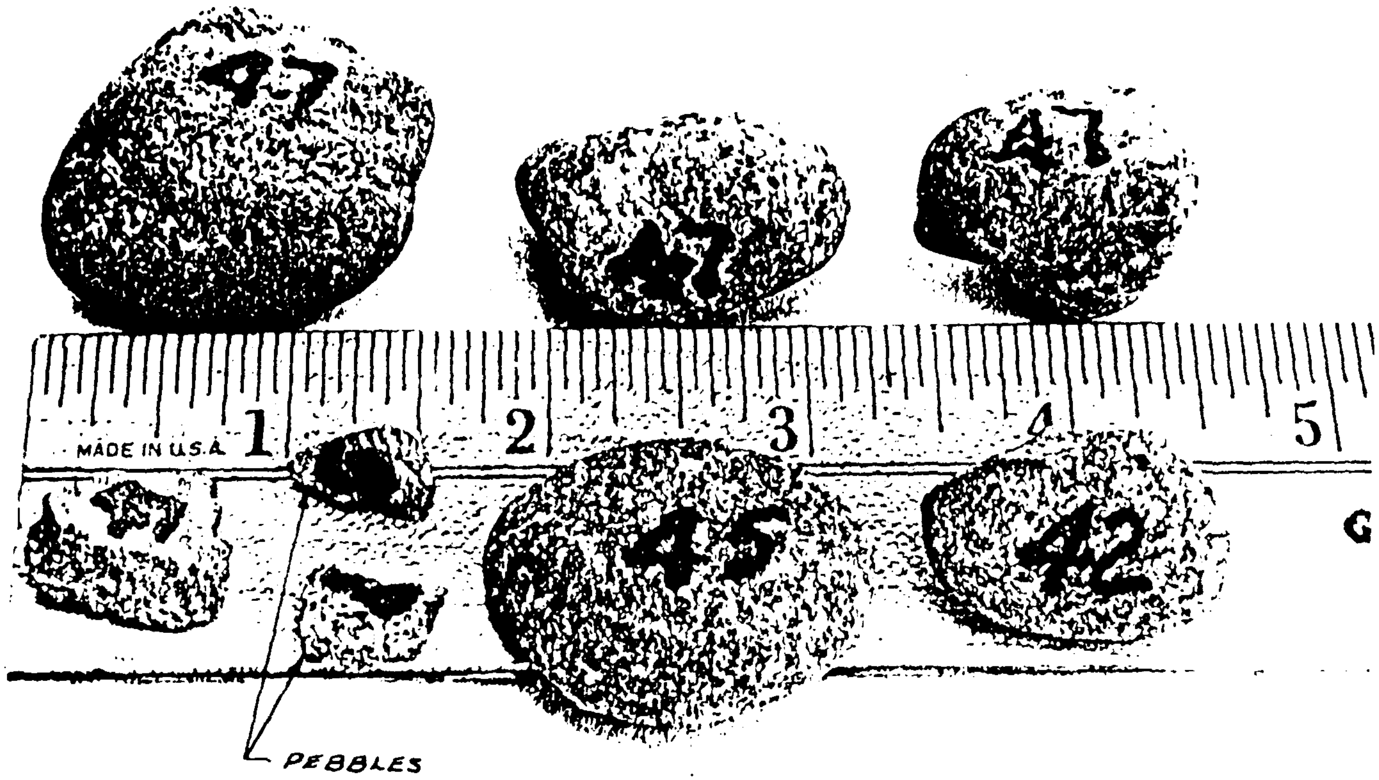

Figure G-9. Rocks and Pebbles.

usually thrown high enough to become entrained in the engine airstream. However, on gravel runways the vortex tends to dig a depression on the runway surface, and when the objects are centrifuged out they are thrown up in front of the engine by the funnelling action of the depression and will enter the engine. Experience has shown that vortices are not formed above approximately 20 knots.

Associated with foreign object damage is the probability of the engine sucking up sand and dirt from the ground. This type of ingestion is at a maximum when the engine is operated at takeoff thrust setting in a static condition.

b. Conclusions

(1) Aerodynamic ingestion has not been a major cause of engine foreign object damage.

(2) Ground clearance of the inlet is not in itself a major indicator of the "vacuum cleaner effect" of an engine installation.

(3) With respect to sand and dirt ingestion, ground plane Mach number is a relevant indicator.

(4) Considering the minimum nacelle to ground clearances, a 17.5 inch landing gear extension on GE13 powered Model 707 would provide an acceptable configuration.

(5) Use of "blowaway jets" or vortex dissipators is not considered to be conclusive with respect to improving foreign object damage engine removal rates.

(6) The major causes of foreign object damage are bird ingestion and debris thrown up during ground operation by thrust reverser action or by other aircraft.

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APPENDIX H

NAVAIR AIRTASK

APPENDIX H

NAVAIR AIRTASK

1. CANCELLATION, REFERENCES, AND/OR ENCLOSURES

Ref: Dynamics Research Corporation Publication E-4026U, Technical Information Retrieval and Analysis System for the FT30-P-412A Turbine Engine, Contract No. N00019-76-C-0506, dated 20 January 1977.

2. TECHNICAL INSTRUCTIONS

a. Title

F-14A Nosewheel Foreign Object Deflector; Technical Evaluation of (USN).

b. Purpose

The purpose of this work unit is to determine feasibility of a nosewheel deflector for engine FOD reduction.

c. Background Information

The F-14A aircraft has proven to be susceptible to engine Foreign Object Damage (FOD). Fleetwide in 1976, FOD accounted for 26 percent of all flight line unscheduled maintenance actions, 24 percent of all unscheduled engine removals, and 8 percent of all mission aborts (Reference above). The possibility exists that FOD is being kicked up by the nosewheel tires and drawn into the engines while the aircraft is taxiing. In an effort to test the theory, NATC has designed and fabricated a nosewheel fender to withstand wind loadings encountered in flight. Other critera such as tire blowout, tire swell during takeoff and landing, tire changing, etc., formed the bases for the fender design. A drop check has been performed and the fender fits inside the nosewheel well.

d. Detailed Requirements/Cost Estimate

All tests prescribed under this work unit are to be performed at the Langley Research Center, Hampton, Virginia, utilizing the Landing Loads and Traction Facility.

(1) Perform simulated taxi-tests with an F-14A nosegear assembly which is taxied over known FOD at various speeds.

(2) Repeat paragraph 3d(1) tests with the nosewheel deflector installed.

(3) Document FOD spray pattern envelope for the nosewheel tires, both with and without the deflector, utilizing high speed photography techniques.

Project Engineer: Mr. P. M. Matis.
Telephone: 692-2420.

e. Detailed Program Plan

Not applicable.

f. Field Activity Contact

Mr. Gary Rasponi, Code SA-52.

g. Headquarters Technical Support

Mr. H. J. Guidry, AIR-530321.
Mr. J. C. Glista, AIR 530321A.

3. SCHEDULE

a. Starting Date: Upon receipt of the work unit.

b. Completion Date: 1 September 1978.

4. REPORTS AND DOCUMENTATION

a. Report

A message report followed by a final report is to be sent to AIR-530321B.

b. Requirements for Future Planning Information

Not applicable.

5. CONTRACTUAL AUTHORITY

Not required.

6. SOURCE AND DISPOSITION OF EQUIPMENT

a. NATC will supply the nosewheel deflector and will retain possession after testing is completed.

b. Naval Air Rework Facility, Norfolk, Virginia, will supply the nosegear assembly which will be returned after completion of tests.

7. AIRCRAFT REQUIREMENTS

Not applicable.

APPENDIX I

F-14 FOREIGN OBJECT DAMAGE TEST
LANDING LOADS TRACK FACILITY (LLTF)

APPENDIX I

F-14 FOREIGN OBJECT DAMAGE TEST LANDING LOADS TRACK FACILITY (LLTF)

1. BACKGROUND

Testing with the F-14 nose landing gear and tires was initiated on 17 April 1981 at the NASA Langley Landing Loads Track Facility (LLTF) under Task Order from NATC Patuxent River, Maryland. The tests observed by BDM were conducted on 28 May 1981 and represented the 31st and 32nd runs of the planned 38 to 40 runs. A variety of FOD configurations was used at different velocities. The speeds ranged from fast taxi (25K), to the LLTF speed limit which is near F-14 take off speed (120K). Performance at different tire pressures was also examined (105 to 350 psi), but most runs were conducted at 300 psi. Crushed stone provided by AFESC was distributed on the track at prescribed densities and depths varying from 3/4 inch to 1-3/4 inch deep (Figure I-1). This simulated different crater repair surfaces. The various forms of other FOD, nuts, bolts, washers, wire, connectors, and high visibility rocks (painted red for camera identification), were placed on the track at specific points for recording accuracy. The number of foreign objects, especially the nuts and bolts, and their proximity to each other greatly exceeded the experienced norm. For example, the distribution on some runs was about 15 to 20 objects per square foot.

Both of the tests witnessed, as well as some of the earlier runs, were executed under flooded conditions (.5 inch to .65 inch of standing water). The total weight applied to the landing gear strut was 8500 lbs of hydraulically applied weight. The entire run was filmed, first, by stationary cameras strategically placed along the track and, second, from a battery of three to four motion picture cameras aboard the carriage. The front view of the tires was captured by a camera positioned on a tripod boom located ahead of the tires (as shown in Figure I-2). Two other cameras were adjusted to film the area immediately above and behind the tires and other cameras were positioned on each side of the cages to capture the broad angle spray.

2. SUMMARY OF OBSERVATIONS

A general summary of test criteria and conditions is shown in Table I-1. This information was given to BDM by Mr. Bill Vogler with the qualification that it represents preliminary, unofficial records of the testing. His assessments and observations provided a valuable insight into FOD (or lack of FOD) generated by the F-14 nose gear. This is probably representative of other fighter-type aircraft and, therefore, permits some generalizations to be made. The following are some conclusions drawn from the test data provided, observations of the tests, and discussions with Mr. Vogler.

Figure I-1. Crushed Stone Distribution for F-16 Nose Landing Gear Test.

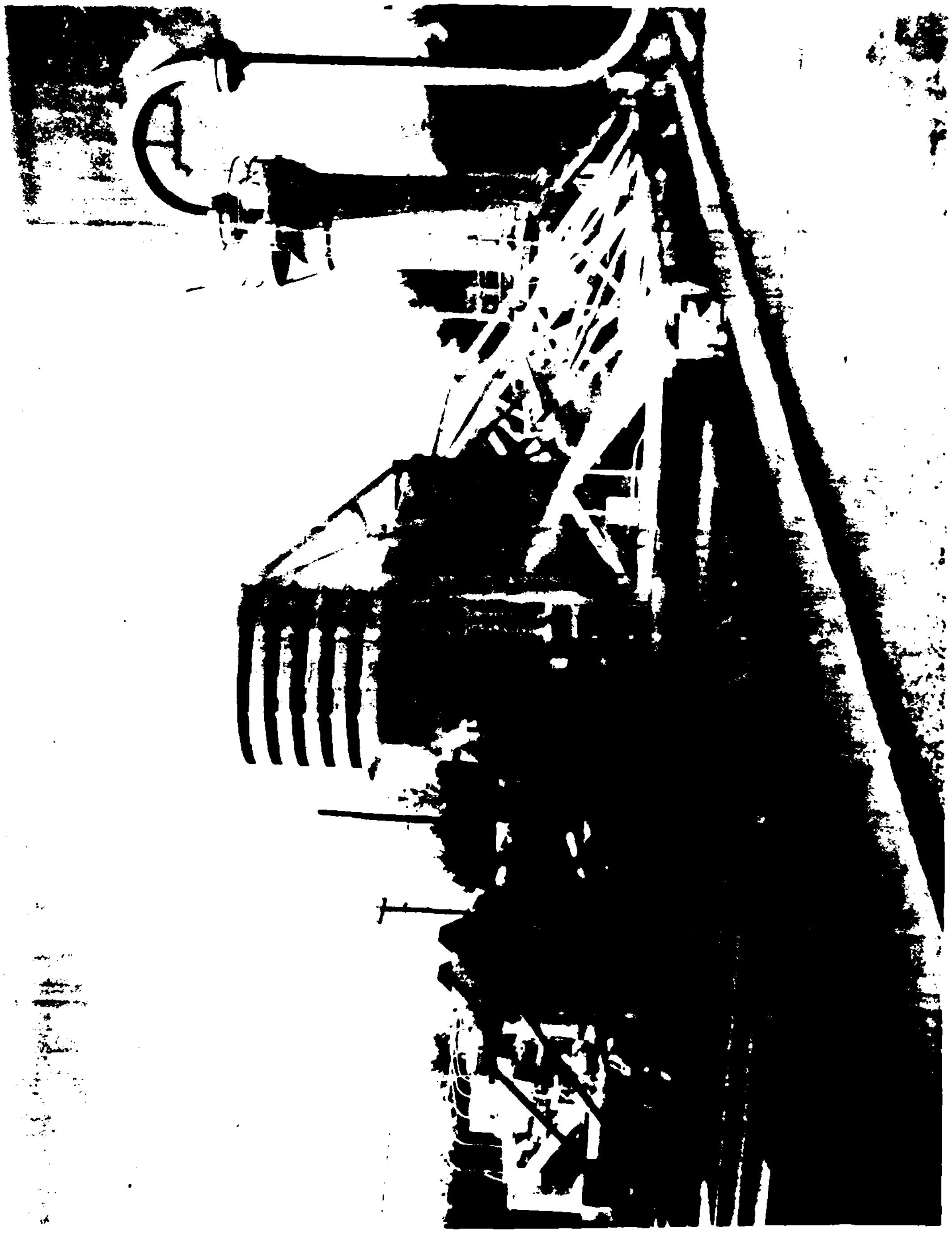

Figure I-2. NASA Langley Test Facility.

TABLE I-1. F-14 FOD TEST RUN LOG.

DATE	SPEED(K)	FOD MATERIAL CONFIGURATION
4-17-81	38	NO F.O. - LOW SPEED CHECKOUT RUN
4-21-81	102	NO F.O. - HIGH SPEED CHECKOUT RUN
4-22-81	66	THREE 15' LONG PILES OF CRUSHED STONE SPACED 35' APART STARTING
4-23-81	84	AT 700' DOWN TRACK TO 815' DOWN TRACK. EACH SUCCEEDING PILE
4-23-81	30	1/4" DEEPER UP TO 1-1/4 DEEP
4-23-81	29	THREE 15' LONG PILES OF CRUSHED STONE SPACED 35' APART STARTING
4-29-81	58	AT 700' DOWN TRACK TO 815' DOWN TRACK. EACH SUCCEEDING PILE
4-30-81	82	1/2" DEEPER UP TO 1-3/4" DEEP
4-30-81	108	
4-30-81	118	
4-30-81	90	
5-1-81	61	
5-1-81	30	
5-4-81	117	FLOODED RUNWAY - NO F.O. - 0.5 TO 65" DEEP
5-4-81	90	
5-6-81	58	
5-6-81	27	
5-12-81	55	FOD DISTRIBUTED AS FOLLOWS:
5-12-81	91	700'-715' HIGH VISIBILITY (RED ROCKS) FOD
5-12-81	117	800'-850' MISC. NUTS AND BULTS
5-13-81	115	900'-925' WIRE
5-13-81	89	950'-970' BRAKE PARTS
5-13-81	59	1000'-1050' ASPHALT AGGREGATE

TABLE I-1. F-14 FOD TEST RUN LOG (CONCLUDED).

DATE	SPEED(K)	FOD MATERIAL CONFIGURATION
5-14-81	58	
5-14-81	92	
5-14-81	118	
5-15-81	118	
5-15-81	90	
5-18-81	62	FOD DISTRIBUTED AS FOLLOWS:
		700'-715' HIGH VISIBILITY (RED ROCKS) FOD
		830'-850' MISC. NUTS AND BOLTS
		900'-925' WIRE
		950'-970' BRAKE PARTS
		1000'-1050' ASPHALT AGGREGATE
5-18-81	90	FLOODED RUNWAY 650'-850' AND 0.5" TO 0.65" DEEP
		700'-715' RED ROCKS
		740'-750' WIRE
		765'-800' ASPHALT AGGREGATE
		810'-820' BRAKE PARTS
		830'-850' MISC. NUTS AND BOLTS
5-21-81	117	FLOODED - F.O.D. MATERIAL LEFT FROM RUN 30
5-26-81	93.5	FLOODED RUNWAY
5-26-81	118	FLOODED RUNWAY
		720'-740' VERY SPARSE RED ROCK
		780'-835' BOLTS/NUTS/AGGREGATE MIXTURE; LIGHT COVER
		825'- BRAKE PARTS

a. Tests over a heavy coverage of crushed stone caused crushing of the stone particles and created about a 1/2 inch rut.

b. Most of the gravel collected in the baskets was less than 3/4 inch in diameter. Most engines would probably ingest several pieces without appreciable damage.

c. The large nut-bolt population had very little effect on the amount of debris collected from a dry surface.

d. The total number of objects collected in the baskets increased significantly when the surface was flooded. Films showed that high visibility rocks were entrained by the water.

e. Despite the flooding and the large amount of hard debris, there was a surprisingly small number of objects of any appreciable size collected (8 to 10) in each basket.

f. The tires incurred the most severe damage, especially at high pressure. Several bolts were embedded in the tires and two large gashes were noted.

g. Most of the foreign objects harmlessly bounced off the under side of the carriage. Some were squirted into the pits on each side. Very little, if any, went outside the track boundary (about 25 feet across).

h. The fender modification seemed to have little or no effect on the FOD incurred. It did change the spray pattern somewhat.

i. Strain and impact tests done in conjunction with the FOD testing revealed that three gravel humps 1-3/4 inches to 2 inches high and set 35 feet apart, made no appreciable difference to the gear. All of the impact was absorbed by the tires.

j. The worst load condition occurred in an earlier F-4 wheel test during which the carriage was accelerated over a 2-1/4 inch concrete stud. The tire again absorbed most of the deflection, but the force was almost three times the steady state load (approx. 70,000 lbs).

k. Most objects of a size, density, or weight capable of damaging the exterior airframe were not appreciably disturbed. They were pushed laterally away from the tire at less than damaging speed or force.

A final observation is that an aircraft engine operating at full afterburner condition behind the spray may well have changed the results. This and several other realistic, operational conditions should be considered if one wishes to determine conclusively the FOD vulnerability of most aircraft engines. The NASA Langley LLTF should be an excellent test site for examining the economic aspects of some of the questions raised by this study.

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